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DEVELOPMENT OF ELECTRICAL SWITCHGEAR FOR SPACE NUCLEAR ELECTRICAL SYSTEMS

Prepared by
GENERAL ELECTRIC
Cincinnati, Ohio
for Lewis Research Center

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FOREWORD

The work described herein, which was conducted by the Space Power and Propulsion Section, Missile and Space Division, General Electric Company, was performed under NASA Contract NAS 3-6467. Program Manager for General Electric was A. H. Powell, who also edited this report. Technical Manager for NASA was E. A. Koutnik of the Space Power Systems Division, NASA-Lewis Research Center, Cleveland, Ohio. The report was originally issued as General Electric document R67SD3012.

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I. SUMMARY

High capacity circuit breakers and contactors are needed for future large spacecraft systems with 500 to 1000 KWe power supplies. Based on the latest experience on utility and industrial systems, a vacuum interrupter appears to be the simplest means of obtaining suitable performance in a space environment.

The feasibility of power interruption in a vacuum capsule in a space environment of 1000°F ambient temperature had been previously investigated, and with this background, pre-flight prototype single pole breakers and contactors have now been designed, built, and extensively tested.

The breaker, rated 1000 volts, 600 amperes, 2000 cps, for main system protection, and the contactor, rated 10,000 volts, 10 amperes, for propulsion engine switching, have been mechanically and electrically tested. Overall performance has been determined in a preliminary way, and successful completion of a 1000-hour endurance test in the 1000°F and 10^{-6} (or lower) torr pressure has given confirmation of the feasibility of the vacuum switchgear for large space systems.

II. INTRODUCTION

Vacuum interrupter switching devices for application in conventional power, utility, industrial, and radio transmitter switching systems have been used extensively for a number of years and have proven to be very satisfactory devices providing fast, reliable interrupting characteristics. Such vacuum devices are not suitable, however, for nuclear space power electrical systems which operate at temperatures as high as 1000°F and in a space vacuum environment. The materials used would be incapable of withstanding the high ambient temperatures and typical actuating mechanisms of existing vacuum switches, which include rolling or sliding surfaces, would seize or weld in the long-term space vacuum environment.

This report describes the design, fabrication, and performance of vacuum interrupter switchgear which is under development for operation at 1000°F (538°C) in a vacuum of 10^{-6} torr or lower pressure. In order to prove the technology and to provide experience toward fabrication of flight prototype hardware, under this contract needed materials and processing techniques were developed and the following devices were designed, built and tested; and are shown in Figure 1.

AC Circuit Breaker rated 1000 volt, 600 ampere, 2000 cps
DC Contactor rated 10 KV, 10 ampere

Extensive tests on the ground prototypes were performed. Endurance tests have been run for 1000 hours looking toward specified life requirements for 10,000 - 20,000 hours of reliable operation.

The circuit breaker rating is such that it would serve as one pole of a three phase breaker in a one megawatt space power system. The contactor rating is such that it could be used for ion engine protection and switching.

Both devices have also been tested for mechanical shock, vibration, acceleration, and acoustic noise, and met the requirements for major spacecraft launch systems.

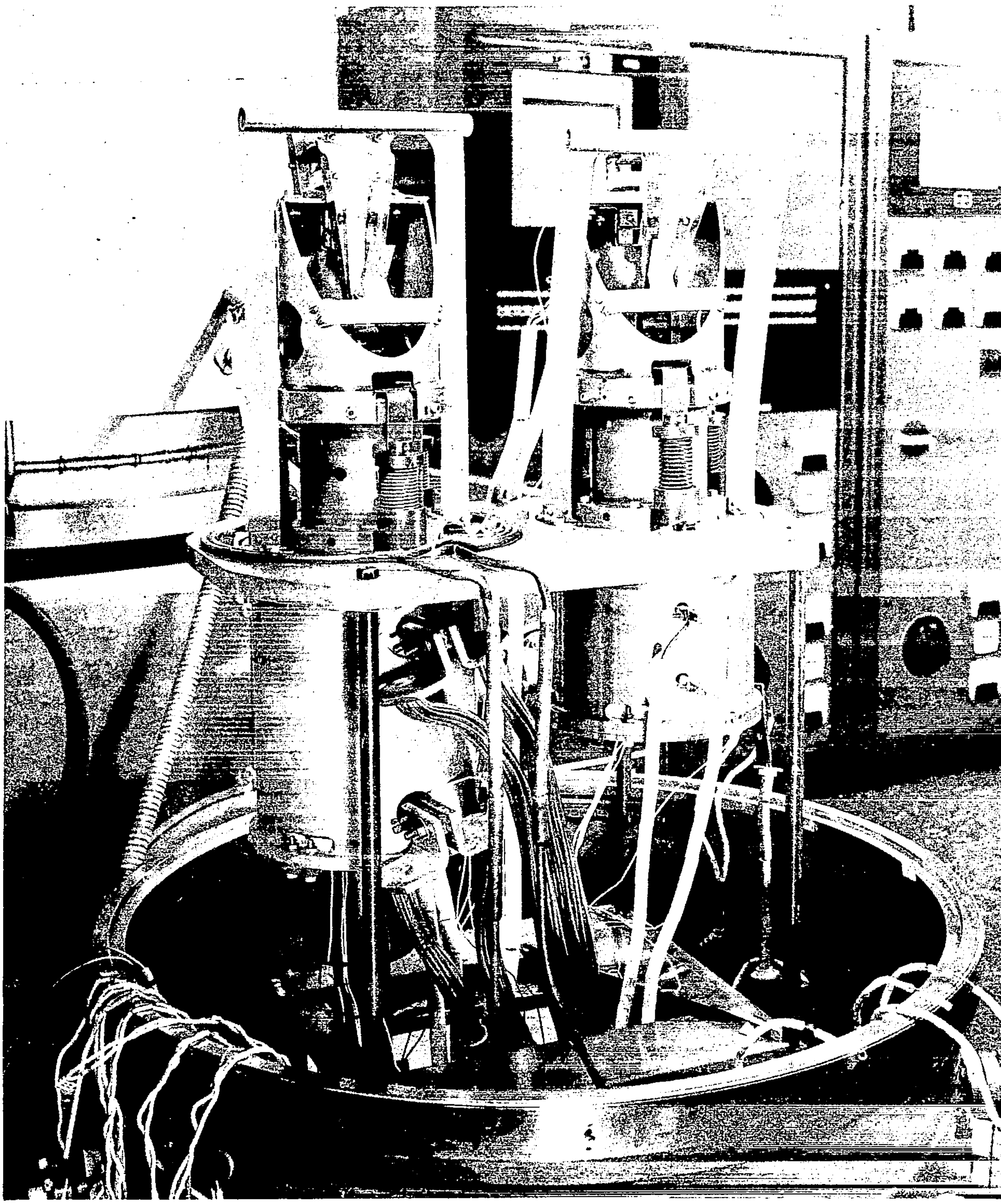


Figure 1. Sample Switchgear Set-Up in Vacuum Tank for Interruption Tests.

Previously, the feasibility of arc interruption with molybdenum contacts in vacuum at temperatures as high as 1300° F was demonstrated by tests reported in NASA CR-54247. The work on this contract refined the information available on switchgear under space conditions and provided the background needed for further design improvements and long-time space operation.

III. DEVELOPMENT OF THE SWITCHGEAR DESIGN

The transition from the basic vacuum interrupter capsule, which was an easily demountable test unit, used in Contract NAS 3-2546, to two working designs, has been a major task of this program. The effort required that a design concept be developed and that proper materials be selected for all parts. Then the vacuum interrupter and mechanism had to be designed in all details, so that with these basic parts both the AC breaker rated 1000 volts, 600 amps (continuous), 1000 to 3000 cps, and the DC contactor rated 10,000 volts, 10 amperes DC, could be produced.

This section of the report will describe the activity involved in obtaining the final design concept and the process involved in selecting the critical material used, especially in the vacuum capsule. It will also discuss the capsule and actuator (mechanism) design in detail.

A. Material Selection

The initial design efforts recognized that the major problem in building a vacuum capsule, the heart of the interrupter unit, was the maintenance of the vacuum at the high environmental temperature if the unit was to be kept sealed in space. Outgassing from the walls of the chamber would be the chief problem to be solved.

1. Capsule Material Selection

To provide additional data on the outgassing problem, a series of vacuum bake-out tests were conducted on the original test capsule. The results of two of the series of tests are shown by the curves in Figures 2 and 3. These gave every indication that there is a maximum amount of outgassing at each temperature, and after a period of time the volume decreases to some lower but fixed value. However, as shown by the calculations below, based on the test sample configuration, a means of removing the gas is essential.

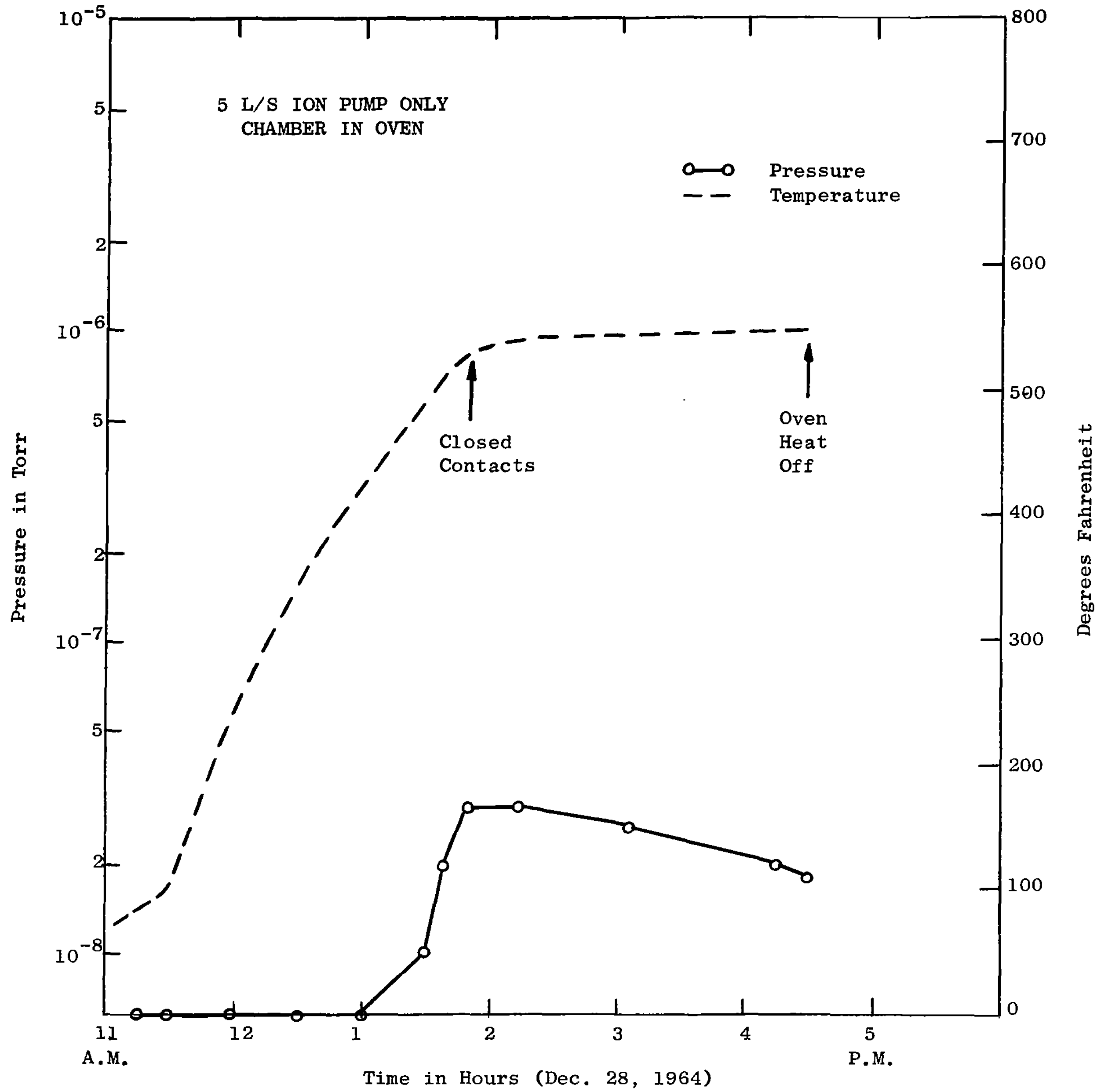


Figure 2. Relation of Temperature (Maximum of 550°F) and Pressure in Vacuum Test Capsule.

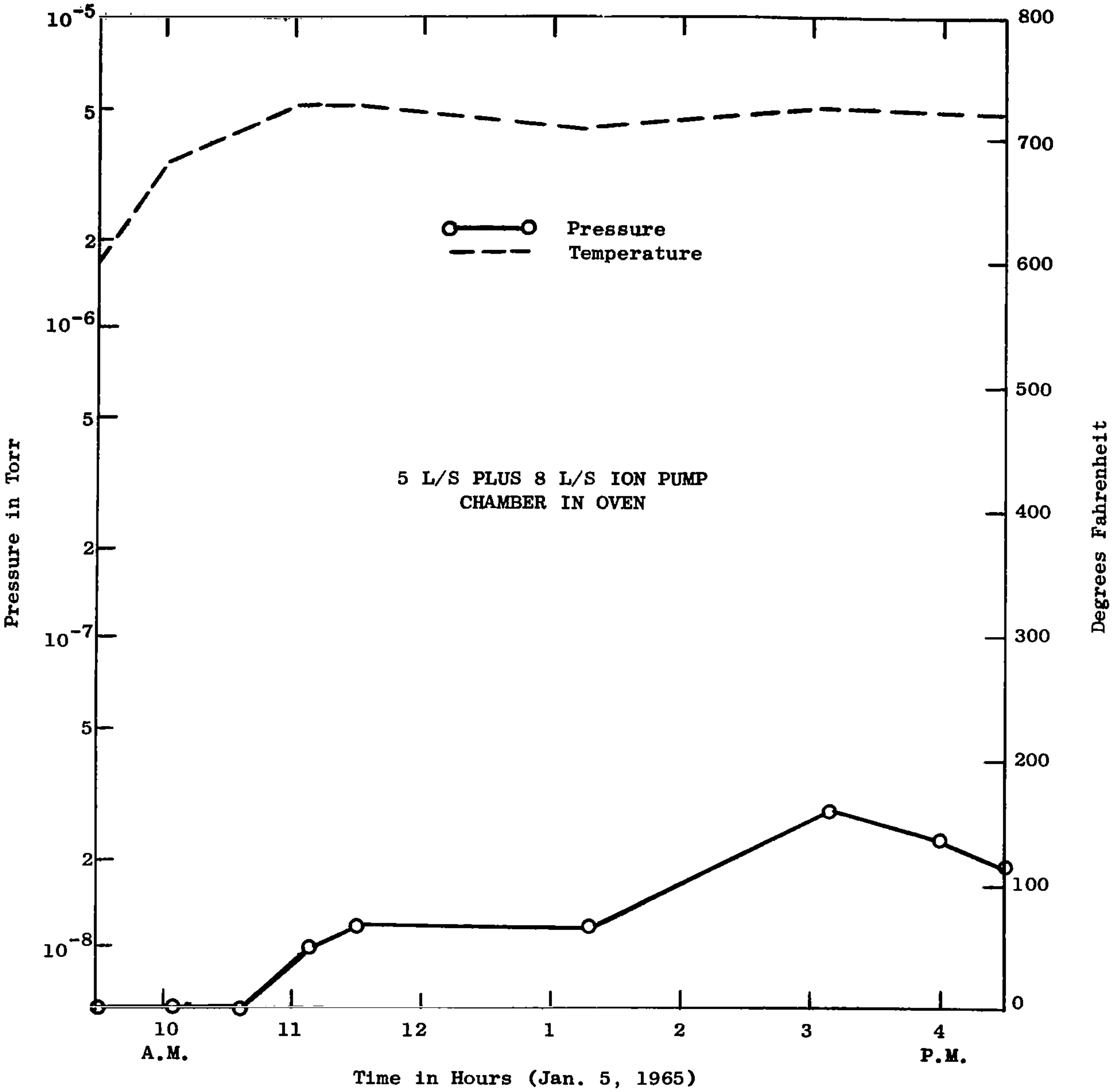


Figure 3. Relation of Temperature (Maximum of 725°F) and Pressure in Vacuum Test Capsule.

A review of gettering materials indicated no proven ones were available for the expected operating temperature range of 1000°F (538°C) to 1200°F (649°C). A small appendage ion pump was also considered. After determining that the device could probably be suitably cooled during test, it was concluded that this was the way to go, if the gas evolved in the capsule could be handled by the candidate pump which had a 0.5 liter/second capacity.

From the curves in Figure 3 it can be concluded that if the temperature had been held constant at 720°F (384°C) the pressure in the chamber would have been constant at approximately 1.5×10^{-8} torr. Under these conditions the outgassing of the walls, or gas influx, (Q_1 per unit time), is equal to the gas pumped (Q_2 per unit time).

With no pumping the gas influx is

$$Q_1 = V \frac{dP}{dt}$$

V = Volume in liters

P = Pressure torr

t - Time seconds

The pumping speed Q_2 is

$$Q_2 = SP$$

P = Pressure in torr

S = Speed L/S

with $Q_1 = Q_2$

$$V \frac{dP}{dt} = SP$$

also $$\frac{\Delta P}{\Delta t} = \frac{SP}{V}$$

The estimated pumping speed of the system is 8 liters per second at 1.5×10^{-8} torr and the volume of the vacuum capsule is 0.5 liters.

Therefore $$\frac{\Delta P}{\Delta t} = \frac{8 \times 1.5 \times 10^{-8}}{0.5}$$

and $$\frac{\Delta P}{\Delta t} = 24 \times 10^{-8} \text{ torr per second}$$

Thus the rate of pressure increase is 9×10^{-4} torr per hour at 720°F (348°C) and, at a pressure of 1.5×10^{-8} torr, the outgassing would raise the pressure to the range of 10^{-4} torr in one hour.

(High purity alumina (98% or better) was selected as the insulating material to keep gas evolution from this source to a minumum).

Continued study of available metals for the capsule indicated that all which could be fabricated without great difficulty would outgas to some extent. However, they should be vacuum processed, have good strength at high temperature, etc. Four were selected for detailed processing and testing to determine the best candidate. The metals tested were as follows:

1) Rodar (a nickel, iron, cobalt alloy) - GE Spec. B7Y36

2) Thoria dispersed nickel - GE Spec. B50T97

3) Titanium (commercially pure) - GE Spec B50T1

4) Molybdenum (arc cast) Spec. AMS7801.

The materials were tested in the following manner:

A. Pieces of the four candidates (especially purchased) were obtained in three thicknesses (0.010", 0.020", and 0.060") and cut into samples 1 cm wide x 4 cm long.

B. Samples of all 4 materials and thicknesses were baked at high (5×10^{-6} torr) vacuum, in compartmentized Cb-1Zr buckets, at 1550°F (838°C) ± 5°F, for 6 and 48 hours.

C. All sample processed pieces, plus samples of the "as-received" material, were tested in a special gas measuring apparatus. The results of these tests show the residual gas that is evolved at various temperatures, even after processing. It is an indication of the amount that would be generated in the capsule over an indefinite period.

A plot of the gas evolved from "as-received" Rodar is shown in Figure 4 while Figure 5 shows the results after the 6-hour bake-out at 1550°F (838°C).

Only Rodar and molybdenum had low enough gas evolution to be serious candidates for the vacuum capsule metal parts. From the fabrication point of view, the Rodar was preferable. Therefore, a detailed analysis was made of the gas evolution to determine if the amount to be expected from the capsule metal surfaces (an estimated total of 400 square centimeters) could be handled by the

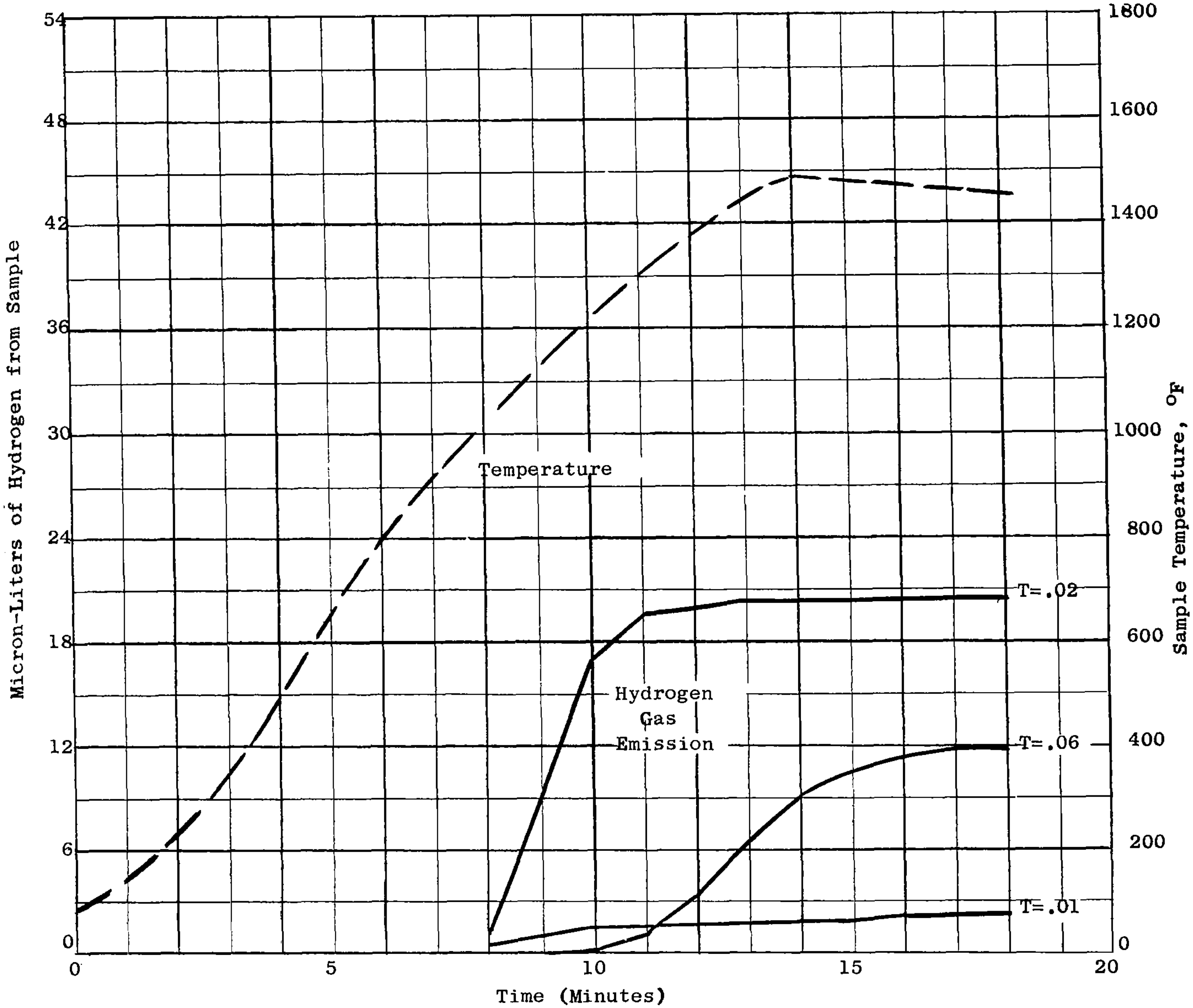


Figure 4. Results of Gas Analysis on "As Received", Cleaned, Rodar.
Material Size: T(inch) thick x 1 cm. x 4 cm.

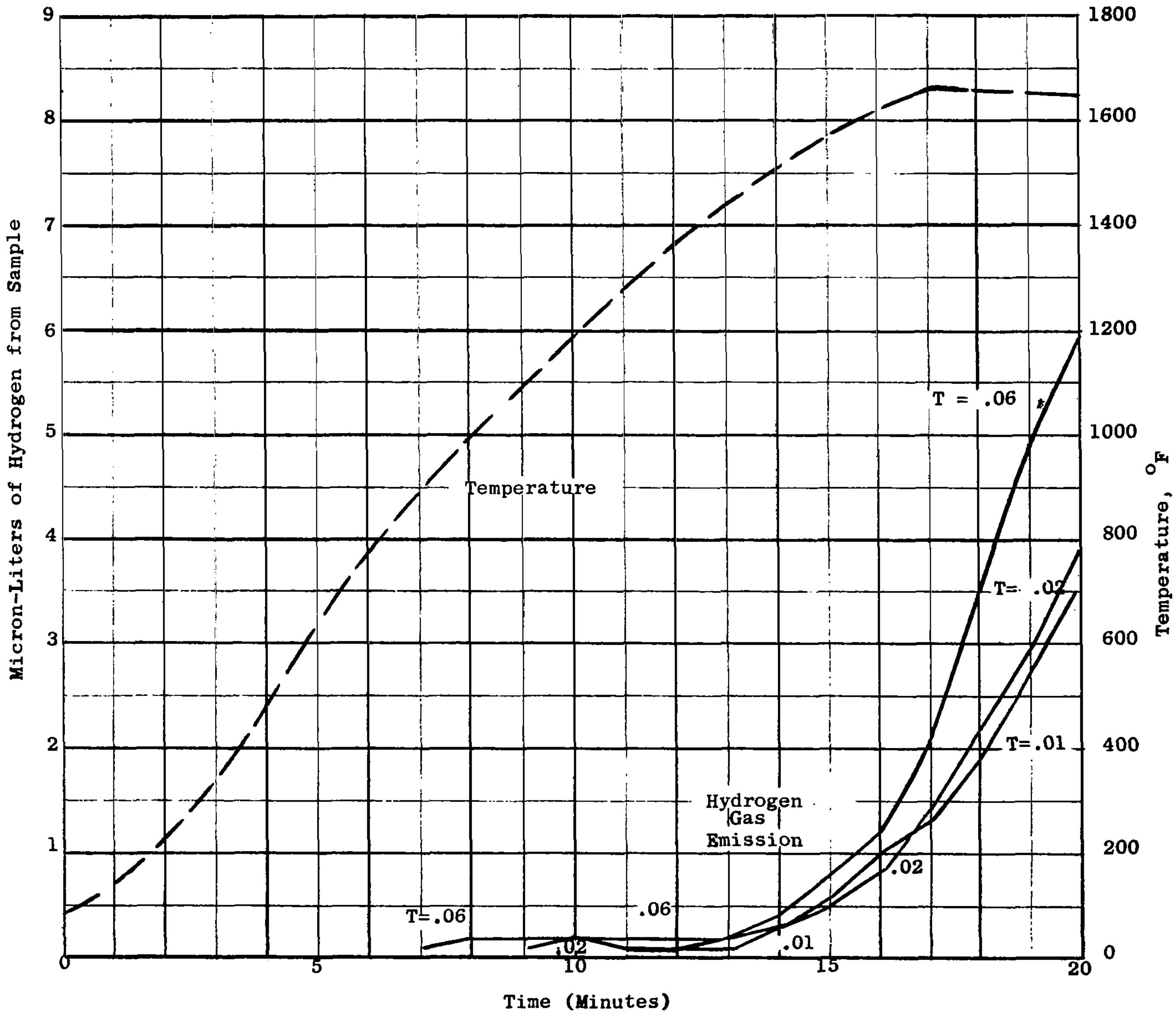


Figure 5. Results of Gas Analysis on Rodar, Baked for 6 hrs. at 1550°F in Vacuum (10^{-8} torr)
Material Size: T(inch) thick x 1 cm. x 4 cm.

0.5 liter per second ion pump. The data are plotted on a summary curve sheet, Figure 6, which shows the hydrogen gas (the major item) evolved from the various samples, on a square centimeter basis, versus the temperature (using the expression 1/T (average) for greater simplicity on the graph paper).

The gas measuring system was not able to give accurate measurements of gas volume evolved at the expected operating temperatures. However, after studying the data obtainable, and the known facts about the evolution of gas as related to time and pressure, it was concluded that an extrapolation to lower temperatures from the higher temperature data could be made to obtain an estimate of the gas that would evolve. Thus the envelope curve of Figure 6 indicates the range that can be expected at the switch operating temperatures. The expected temperature for the majority of the switch metal surfaces was selected as 1112^{o}F (600^{o}C) or 873^{o}K. The $1/T_{av.} \times 10^{3}$ value is 1.15. This shows from the curve a possible range of gas evolution from the Rodar, of 4×10^{-7} to 3.5×10^{-6} micron liters/second.

The surfaces in the switch exposed to the sealed section includes the end pieces, the shield (which was made of molybdenum) and the multiple surfaced bellows. Based on present switch designs and dimensions, it is estimated the total surface that will be evolving gas will be approximately 400 square cm Further reference to Figure 6 will indicate the range of gas evolved from the total switch (400 cm^{2}) and the capacity of a 0.5 liter per second pump.

The conclusion from this data is that if well outgassed Rodar is used for the sealed vacuum switch, a 0.5 liter per second pump will probably handle the gas evolved and maintain the pressure near 10^{-6} torr. On the other hand, if the pump is unable to hold the 10^{-6} pressure, the capacity will be sufficient to hold a pressure below 10^{-5} torr which is still considered adequate for the interrupting requirements of the vacuum interrupter. Therefore, it was decided to use Rodar for the switch metal enclosure parts, and design work proceeded on this basis.

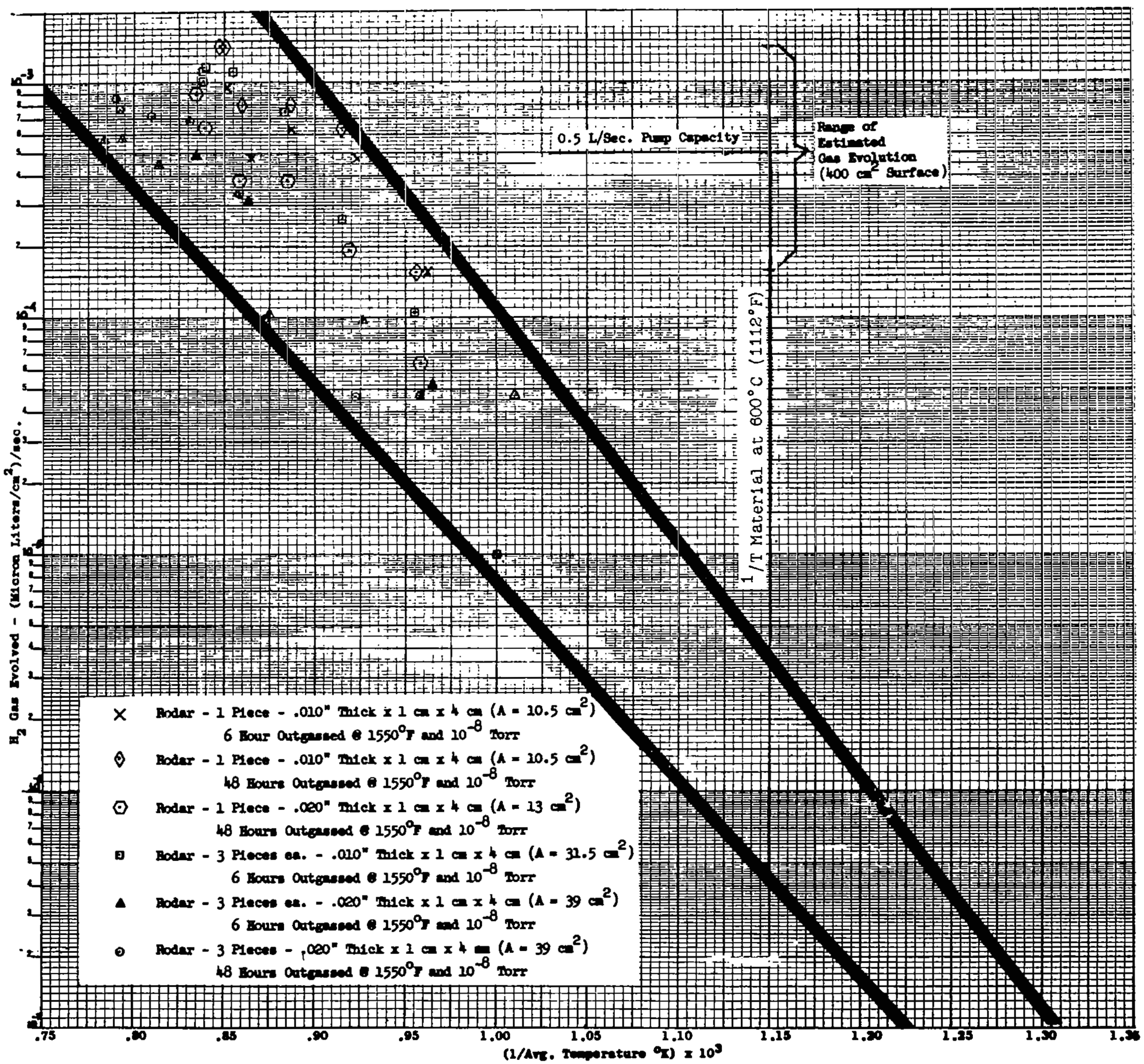


Figure 6. Switch Material (RODAR) Hydrogen Gas Evolution Rate.

2. Contact Material Selection

The original investigation determined that the contacts in the interruption unit should be made of molybdenum. Interruption tests indicated also that their configuration should be approximately 3/4" in diameter. However, additional theoretical study of the behavior and parameters of these contacts under the 1000°F (538°C) temperature were needed to be reasonably sure of good performance under the high AC continuous and momentary currents.

Preliminary studies of contact resistance phenomena showed a high probability of "single point" contact between the hard and nominally plane moly contacts. Under full current conditions this might result in contact melting at a point of contact.

Contact resistance properties are usually defined in terms of an average constriction temperature (which in turn defines the resistivity and mechanical properties) assuming negligible temperature rise over the base electrode near the constriction. This assumption is reasonably valid for low current operation in which the heating is relatively unimportant. It is, at best, a first estimate under high current test conditions. Holm ("Electric Contacts" - book by R. Holm) gives the following expression for the calculation of the supertemperature of the constriction boundary (its elevation over the base temperature of the electrode):

$$\Delta T = \frac{U^2}{8\rho k} \quad {}^{\circ}K$$

U volts contact drop
ρ resistivity ohm cm
k conductivity watt/cm °K

Unfortunately, the contact potential drop U is a function of the super-temperature, through its effect on ρ, and far more critically through its effect on the contact diameter, 2a, as a result of the softening of the contact material, at the constriction under high current flow. It will be recalled that the radius of the contact point a was defined by:

$$a = \sqrt{\frac{P}{\pi n H}} \quad \text{cm}$$

P contact load KG
H "hardness" yield stress KG/cm^2
n number of equal contact points

where n = 1 for all practical purposes in the molybdenum contact system. The hardness of the molybdenum contacts falls sharply as temperature rises to $500^{\circ}K$ ($440^{\circ}F$) and then much more slowly until the softening point is approached at about $1300^{\circ}K$ ($1882^{\circ}F$). The contact resistance was then shown to be $R = \rho/2a$, leading to a contact voltage drop of:

$$U = \frac{\bar{\rho} I}{2} \sqrt{\frac{\pi}{n} \frac{H}{P}}$$ volts where $\bar{\rho}$ is average resistivity in the constriction.

The supertemperature can now be obtained in terms of the mean values of resistivity and thermal conductivity $\bar{\rho}$ and $\bar{k}$, which in turn may be shown to be equal to their value at a temperature 2/3 of the way up from the base temperature toward the supertemperature ($T_o + 2/3\,\Delta T$). For the probable case of essentially single point contact, N = 1:

$$\Delta T = \frac{\pi}{32} \frac{H}{P} \frac{\bar{\rho}}{\bar{k}} I^2$$

I current thru contact amperes

$\bar{k}$ mean thermal conductivity

In the use of this expression, the value of H is rather hard to define. It is necessary to consider the effect of varying hardness (with temperature through the constriction) on the interpenetration of the asperities which constitute the contact region. Since half of the total temperature rise occurs within a distance of less than the radius of the "spot" from the contact plane, the assumption has been made that hardness at the supertemperature maximum may be used to define the contact radius. This will lead to a slightly optimistic (low) contact resistance with an implied increase welding probability. If we take the Wiedeman-Franz law, $\rho k = A\,T$, into account, the expression may be modified to eliminate the large variations in ρ over the temperature range, and lead to the following approximation, assuming $A = (2.6)\,10^{-8}$ and $k = 1.05$ w/cm $^{\circ}K$, with A and K as constants in the 1000 ($1342^{\circ}F$) to $1500^{\circ}K$ ($2220^{\circ}F$) range:

$$\Delta T = \frac{\pi}{32} \frac{H_{eff}}{P} \frac{A}{k^2} (T_e + 2/3\,\Delta T)\, I^2 \quad (T_e \text{ electrode temperature } ^{\circ}K)$$

This equation may best be applied in a series of iterative steps, first calculating ΔT using the value of H_{eff} for an assumed value of $T + \Delta T$ and then correcting this value, as needed, to bring about a balance. In general, as long as the supertemperature is not enough to drive the constriction barrier temperature above the softening point, the value of ΔT will be a function of I^2. If the contact temperature does exceed this limit, however, the sharp reduction in contact resistance, as the asperities settle into contact, will lead to much lower values of ΔT, not very far above the softening point. Of course, if I^2 continues to increase, contact melting, and catastrophic destruction of the electrodes may result. Solving the equation for ΔT in terms of the parameter, $K = \pi H_{eff} A I^2/32 P k^2$ and T_e, the electrode base temperature, we obtain:

$$\Delta T = \frac{K}{1 + 2/3\ K} \quad T_e$$

In the region below the softening temperature $H = (1.3)\ 10^4\ KG/cm^2$ is a reasonable approximation and, for 50# (= 22.5 KG), the expression for K reduces to: $K = (2.6)\ 10^{-6}\ I^2$. This simplification is realistic, as long as K is fractional. At large values of this parameter, the variation in H and A/k^2 must be considered, as seen in Figure 7. If we consider that the constriction temperature is, indeed, the proper level on which to base the identation hardness, the value of K may be scaled from the parameter $H\ A/k^2$ plotted in Figure 7. Thus, at $1500^{\circ}K$ ($2220^{\circ}F$), it will be about $(4.9)\ 10^{-7}$ or about 19% of its low temperature value.

The temperature of the boundary plane in the constriction is given in Figure 8 as a function of the current carried by the contacts and the base temperature established at the electrodes. It will be seen that the supertemperature (increase over the base temperature) follows the quadratic law in the lower temperature region. As the constriction temperature reaches the softening region, the slope of the temperature vs current curve decreases sharply. The supertemperature was calculated for a $1500^{\circ}K$ ($2220^{\circ}F$) constriction temperature to provide the approximation of the curve shown in this region. It may be seen that the electrode base temperature would have to be maintained at very nearly the $811^{\circ}K$ ($1000^{\circ}F$) ambient for the passage of 600 A not to yield an excursion into the softening region.

It is very probable, therefore, that the switchgear will always run into the softening region under overload conditions, and possibly under normal current. The potential welding hazard must be considered, but the lowered

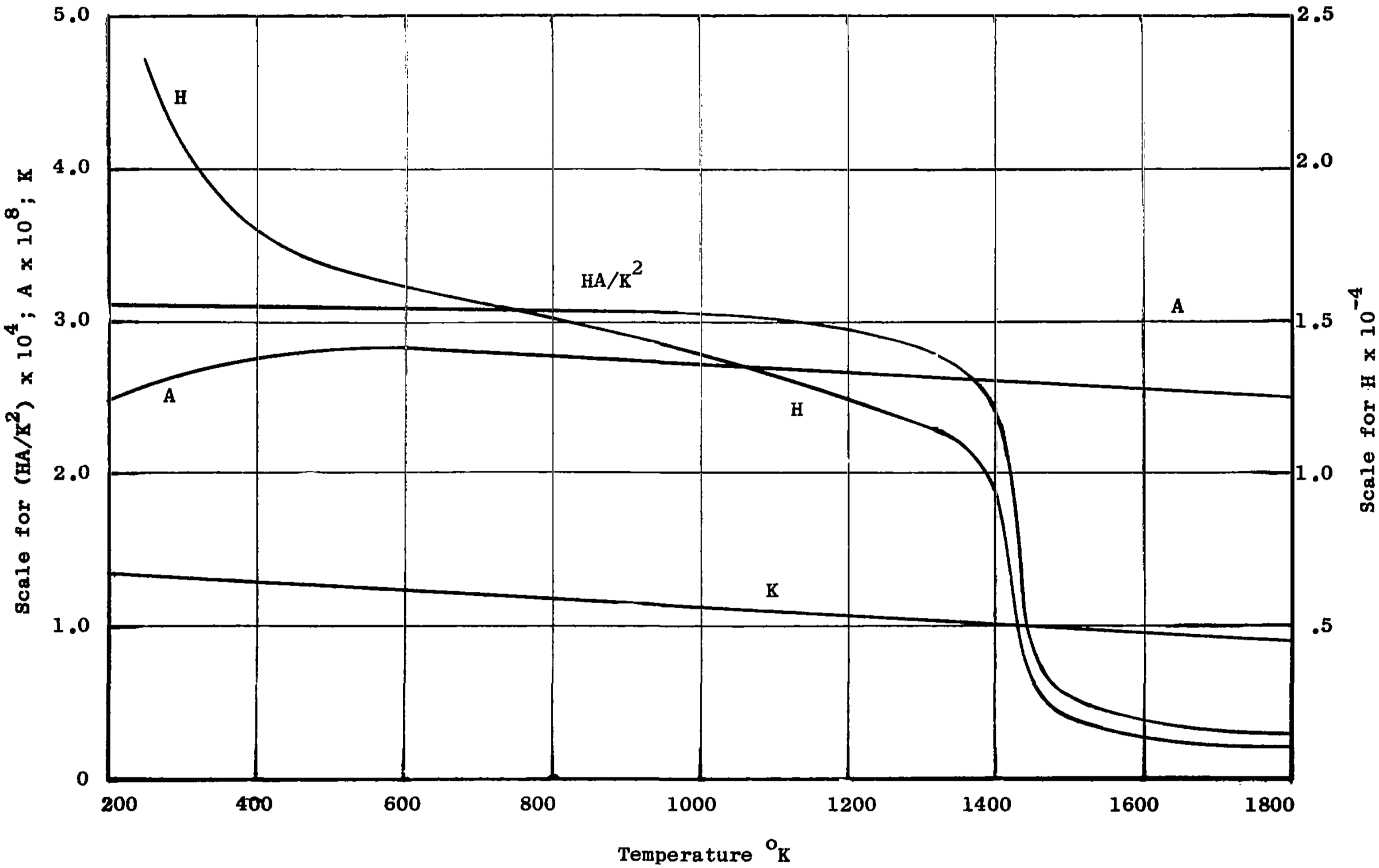


Figure 7. Molybdenum Contact Parameters as Related to Temperature.

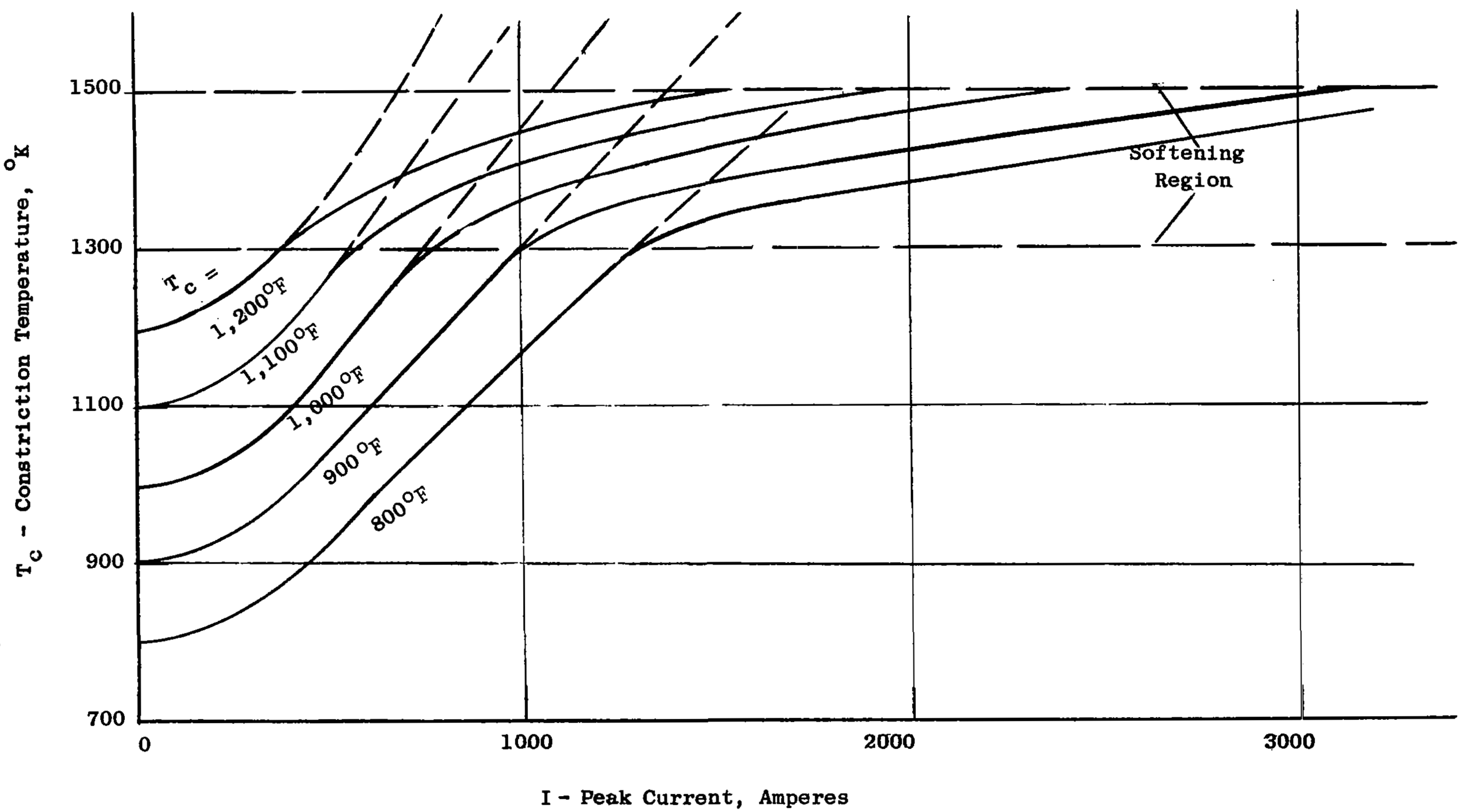


Figure 8. Constriction Temperature Variation with RMS Current.

contact resistance associated with the softened contacts will substantially reduce the heat load on the nominal hard metal of the radiator system. The contact resistance will be somewhat less, if the temperature defined in Figure 8 is used to estimate the resistance. Thus, if the electrode temperature is $1100^{\circ}K$ ($1520^{\circ}F$) and the current is 1000 A, a supertemperature of $400^{\circ}K$ ($720^{\circ}F$) will lead to a constriction temperature of $1500^{\circ}K$ ($2240^{\circ}F$) with a contact resistance slightly in excess of 0.3 milliohms.

In view of the theoretically high temperatures that are possible, a further check was made of contact temperature rise in the original demountable capsule contacts. The results are plotted in Figure 9.

Oven temperatures were gradually raised as the capsule was evacuated. With DC current, the voltage drop was measured and the contact resistance calculated. The final resistance of the contacts, measured at room temperature, was 22.5 micro-ohms, or considerably below the initial resistance (approx. 55 micro-ohms). Opening and closing the contacts re-established the higher resistance. Apparently contact asperite softening took place, but there was no indication of welding. The phenomena will aid in lowering contact resistance and contact temperature rise, which is a definite help in this design.

3. Current Carrying Parts

The AC current carrying parts must be of as high conductivity as possible, and after considering various materials, an oxygen free high conductivity copper was specified for these parts. However, some of these copper parts were required to carry a substantial loading force while being good conductors. For such parts, a recently available material named Amzirc was selected. Amzirc, a 0.15% zirconium dispersed copper, provided appreciable strength even at the operating temperatures.

As part of the investigation of heat transfer problems with the current carrying parts, a sample was made up by brazing a typical molybdenum contact into a copper disk. The surface of the contact was heated with an electron beam, and temperatures at important points were measured. The results are shown in Figure 10. A temperature gradient of about $150^{\circ}F$ was obtained. This indicated

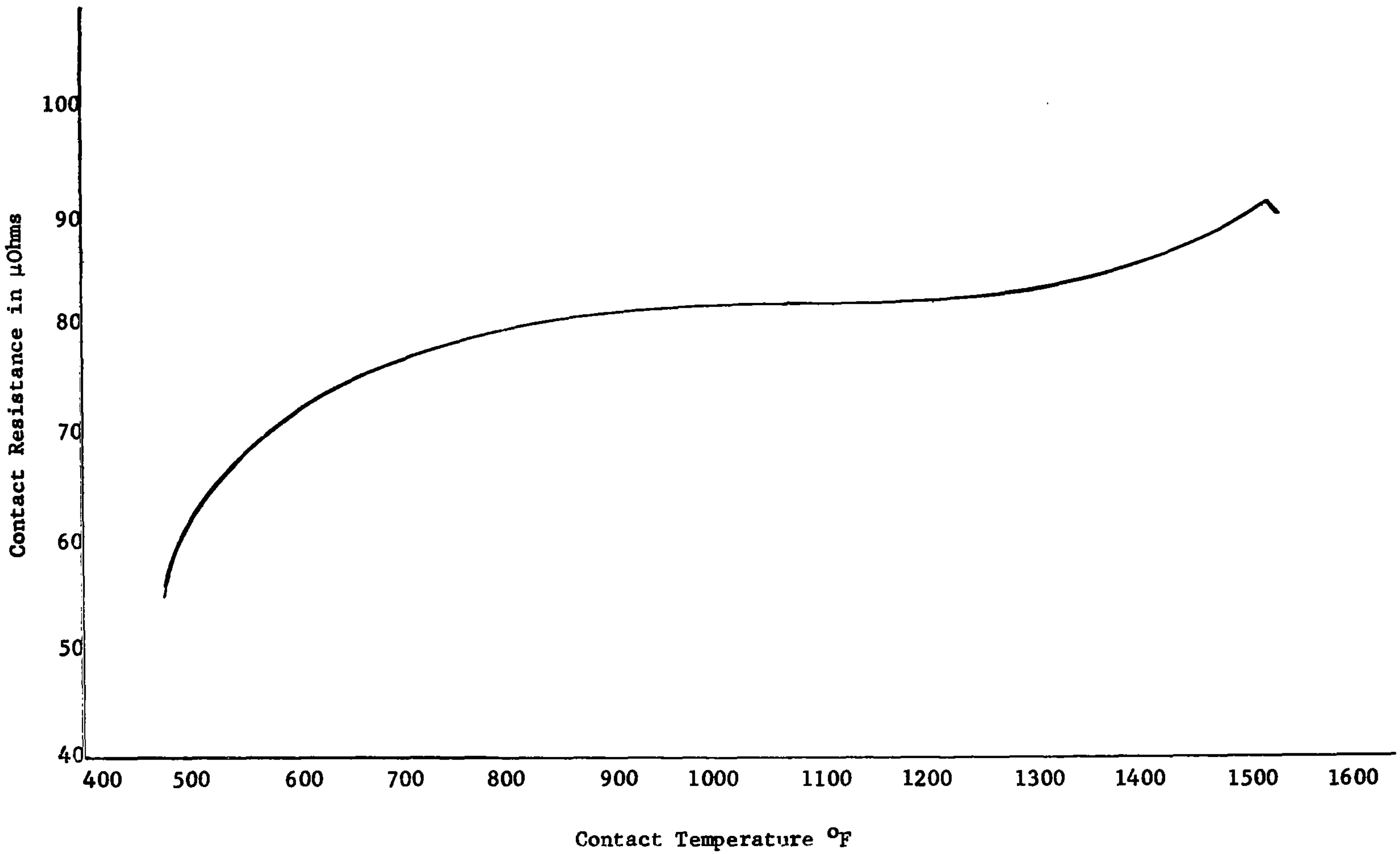


Figure 9. Relationship of Contact Resistance to Temperature of Sample Molybdenum Contacts.

STEADY STATE TEMPERATURE OF BRAZED SAMPLE SWITCH END

	Thermocouple (1) Number	Temperature °F
With Complete Shielding		
Run #1	1	1570
	2	1570
	3	1370
	4	1470
	5	1430
Run #2	1	1540
	2	1570
	3	1420
	4	1450
	5	1420
Without Top Shield		
Run #1	1	1470
	2	1560
	3	1120
	4	1300
	5	1200

(1) Thermocouple Location

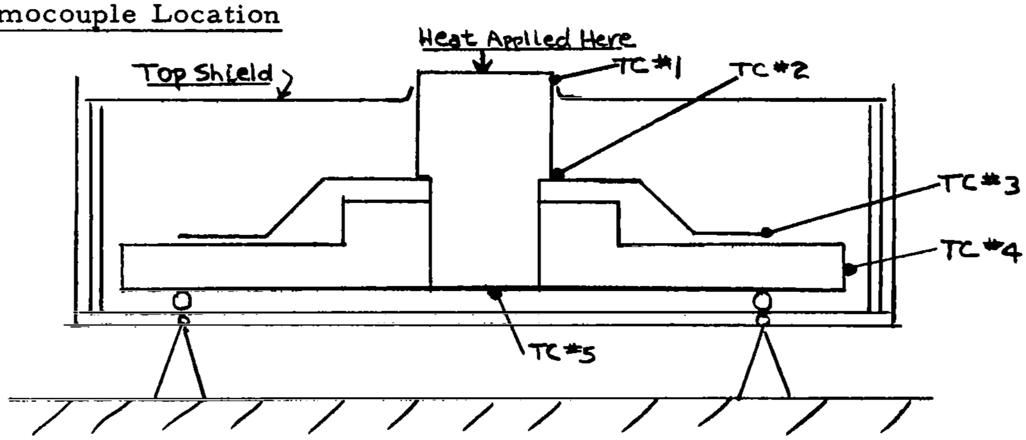


Figure 10. Brazed Sample #1 - Set-Up for Heat Run to Determine Resulting Temperatures.

that contact heat removal was feasible, using the current conducting parts, and radiators to transfer the heat to a lower temperature heat sink.

B. General Design Concepts

Based on the work under contract NAS 3-2546, a three phase AC breaker design and a single phase DC contactor was visualized. However, as layouts and design study work progressed, it became evident that a much simpler and less costly design could be obtained based on a single phase unit for both the AC and DC devices. Furthermore, there would be times when single phase switching of AC breakers in the proposed power systems would be very advantageous.

Therefore, the single pole design concept was adopted, and after considering various configurations, the general arrangement shown in the sketch, Figure 11, was evolved. As will be explained in more detail in subsequent sections of this report, design of the vacuum capsule, the interrupter unit (lower part of sketch) and mechanism (top part of sketch) was carried out as separate projects, based on the overall arrangement shown by the sketch.

The switchgear is arranged to be mounted on a "heat sink" bulkhead surface to provide a place for heat removal. The mounting point was preferably in the center of the device to improve performance under the exacting mechanical test conditions. It was also desirable that the breaker and contactor be mechanically held in the closed position, using little or no power, and the "over-center" toggle mechanism did this very well. The final switchgear design followed the initial concept quite faithfully and this provided a unit which met the various initial criteria, of performance and reliability, and could be the basis for further refinements.

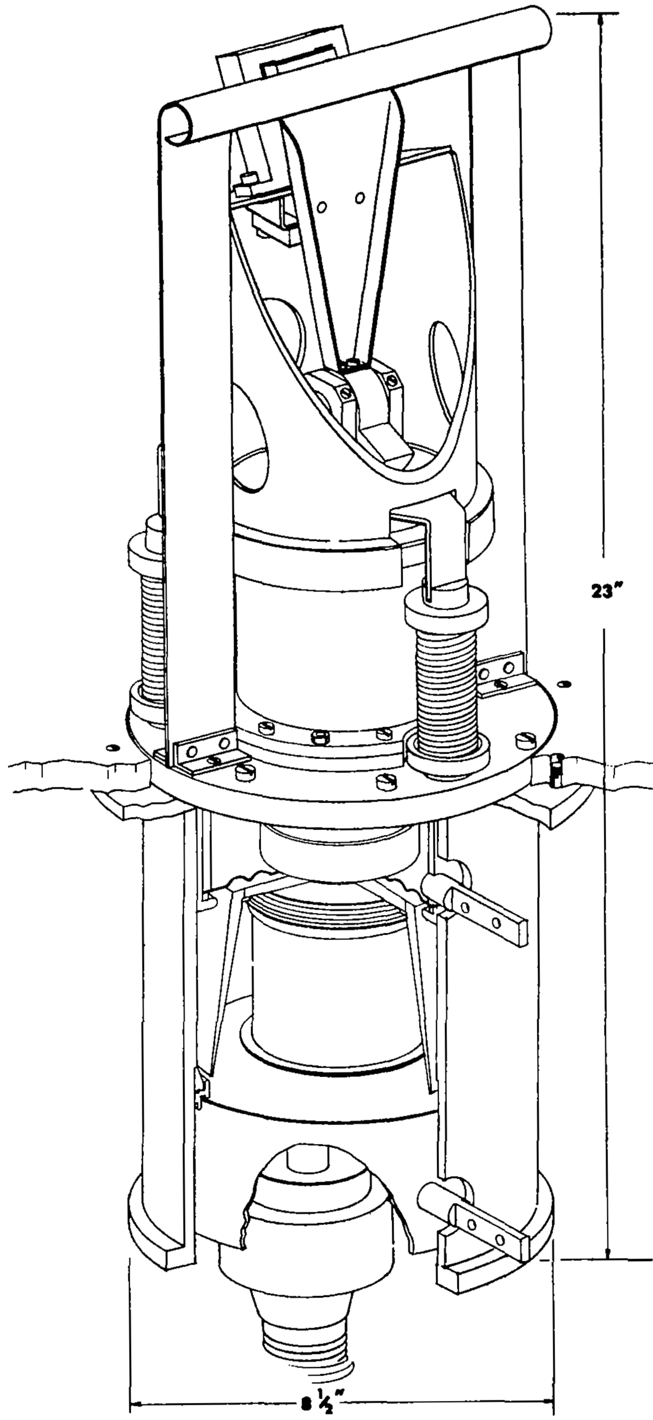


Figure 11. Sketch of Proposed Vacuum Circuit Breaker Showing Actuator (Mechanism) at Top, Attached to Interrupter Unit, (Lower Part, Below Mounting Plate).

C. Vacuum Capsule

1. Conceptual Development

The vacuum chamber used in tests performed under contract NAS 3-2546 was a ceramic enclosure which had end fittings and included a heater to maintain contact temperature during testing. This arrangement was suitable for studying arc interruption problems, but a design suitable for incorporation in a workable piece of switchgear had to be developed on this contract.

A double break design was initially considered, but complexity and size outweighed other advantages, and the single break arrangement shown in Figure 12 was finally selected. This configuration has provision for adding heat transfer radiators for the high current AC unit and expected temperatures during operation are shown in the Figure.

The final vacuum capsule design, which will be discussed more fully in this section of the report, is shown in Figure 13. A photograph of the capsule is shown in Figure 14.

2. Design, Fabrication, and Assembly

The final capsule design, shown in Figure 13, was detailed for fabrication, using the preferred materials developed during the material investigation part of this program. The contacts were made from arc cast, vacuum melted molybdenum. The bellows and all spinnings were made of vacuum melted Rodar sheet. The tube connection for the ion pump was made of stainless steel to simplify welding. End flanges, to which the power connections and radiators (for the AC breaker) are attached, were made from Amzirc (zirconia dispersed copper). The insulation section, consisting of a "build-up" from a series of rings, was made of 99% pure alumina.

The capsule vacuum requires a means for removing the gas which will be evolved at high temperature. The small 0.5 liter/second, triode ion pump was selected for use with the size and configuration of the final capsule design. The pump, however, will not operate at the environmental temperature and therefore during the tests it must be cooled.

To cool the pump, a stainless steel shell was designed to fit around the pump, and a concentric hose was developed to deliver cooling air to the pump,

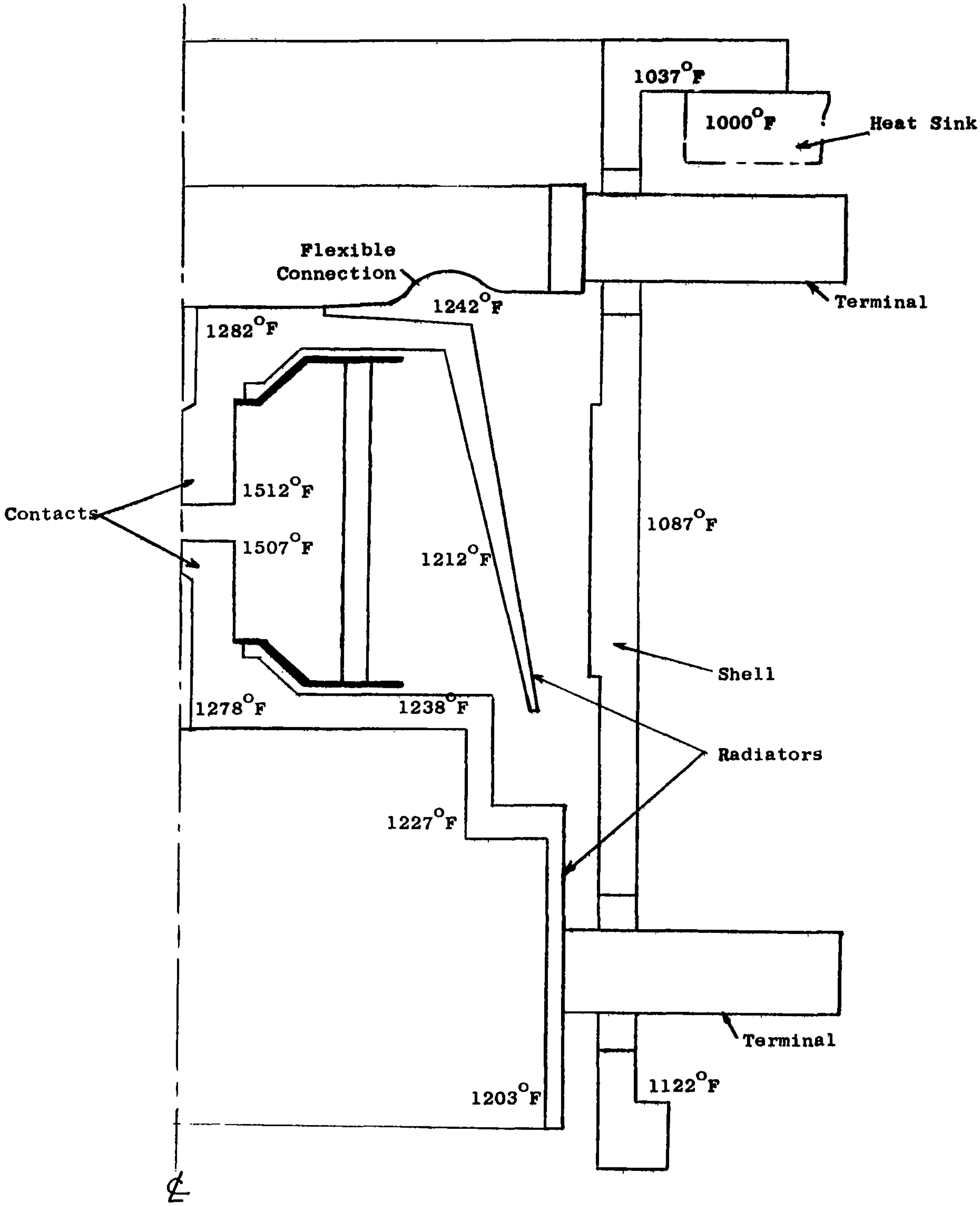


Figure 12. Calculated Contact and Heat Transfer Surface Temperature for Proposed AC Breaker Arrangement.

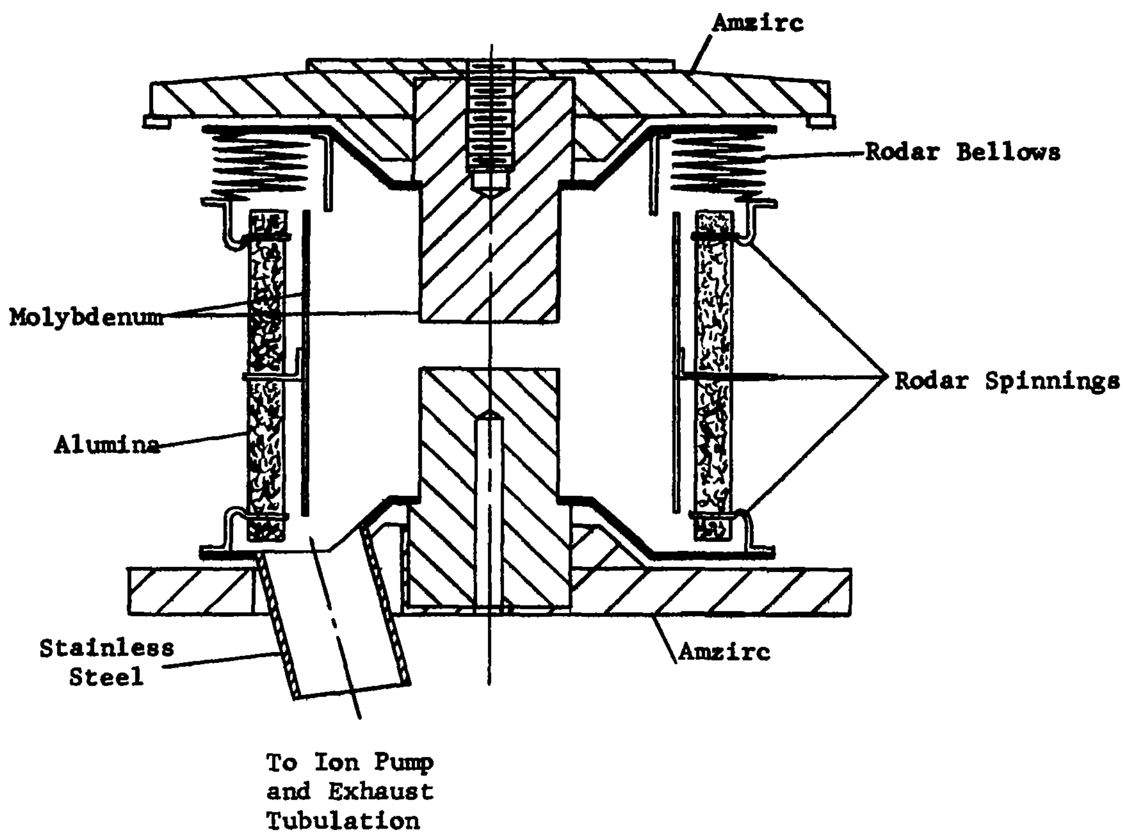


Figure 13. Sketch of Vacuum Capsule for AC Breaker and DC Contactor.

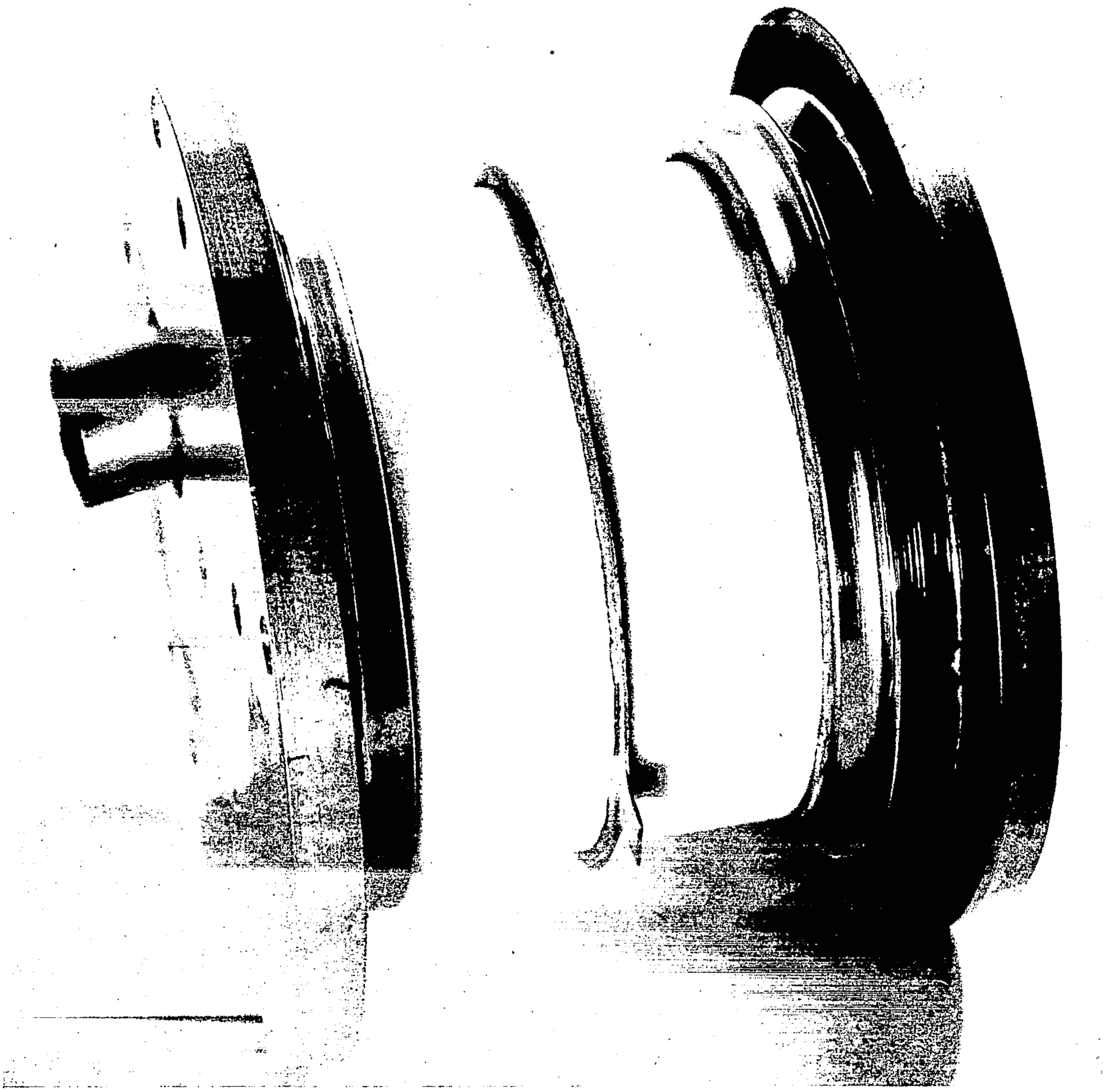


Figure 14. Vacuum Capsule Assembly Prior to Attachment of Ion Pump.

return the warmed air to the test room, and to provide a location for the high voltage pump electrode lead. Suitable heat shielding of the pump improved the results.

The metal parts which were used to make up the capsule end assemblies are shown in Figure 15. The parts were thoroughly cleaned, as described in Appendix A, to remove foreign materials and residues which would cause contamination and outgassing at high temperature in vacuum. Welding of the top and bottom brazed contact assemblies, shown in Figures 16 and 17, to the bellows and ceramic seal assembly, was done inside a vacuum purged tank filled with a 99.95% pure argon atmosphere while held in a rotating fixture. Appendix B gives details of this work, which produced the capsule shown in Figure 14.

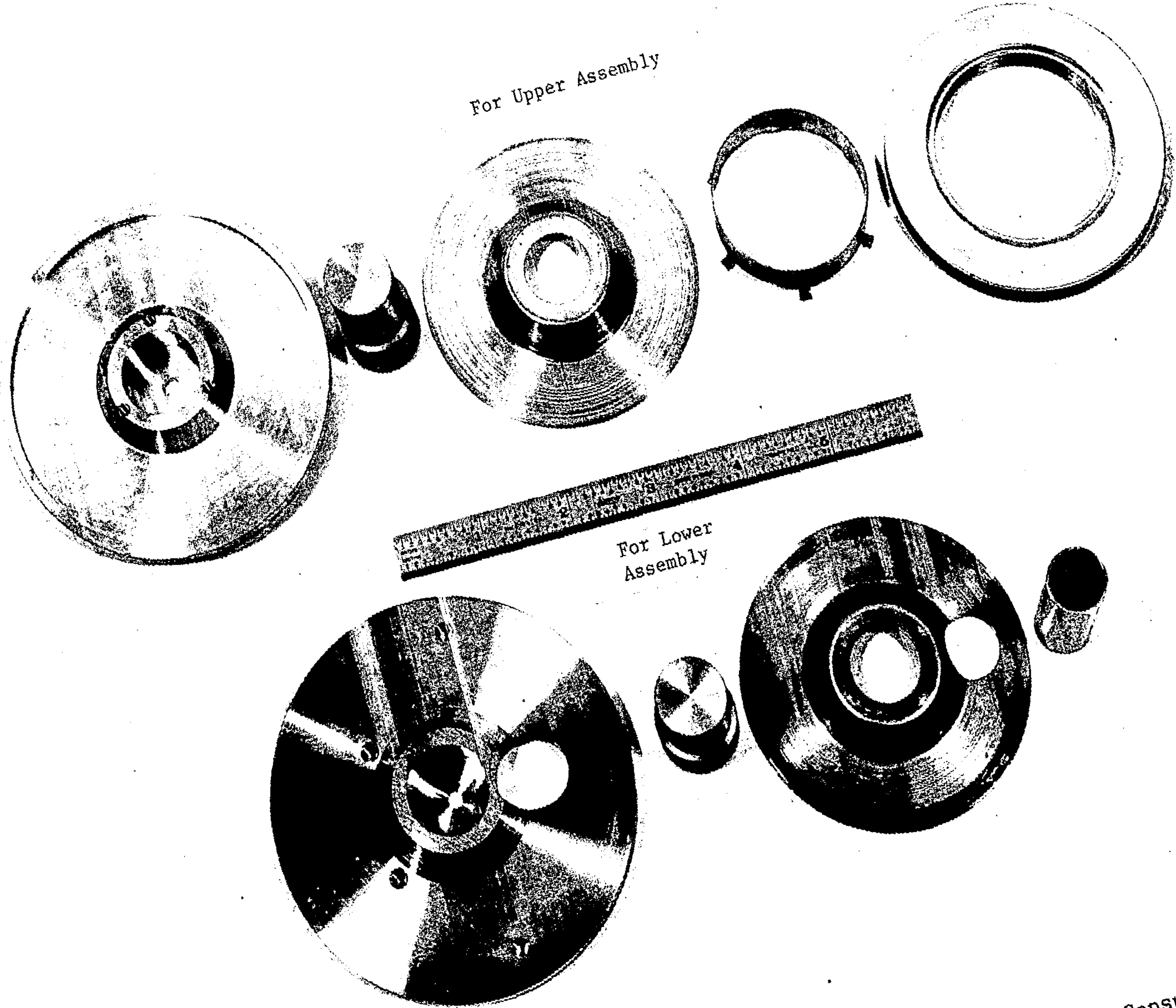
Evacuation, bake-out, and seal-off of the vacuum capsule required the development of special handling, heating, and check-out procedures. A 25 liter per second ion pump, connected to the capsule inside the evacuated bake-out tank, was used for final evacuation, as described in Appendix C.

Some minor leaks were detected after the initial evacuation, but these were sealed with a special compound (made for this purpose) and a tight capsule resulted. The 0.5 liter per second ion pump was able to maintain the vacuum in the capsule at 10^{-6} torr, or lower, pressure during the high temperature tests, indicating that calculations of outgassing rates were correct.

D. Actuator (mechanism)

The initial requirements for the mechanism were based on providing a design which would latch the interrupter in the closed position without using power, would not involve sliding surfaces (including pivot pins), and would operate a 3 pole device. The decision to develop a single pole device reduced the mechanism loading requirements. Investigation of possible pivot designs provided a "flexural" made by Bendix Corp., which consists of two cylinders connected by flat spring members (used preferably in tension). The cylinders move relative to each other by flexing the spring members.

The original toggle linkage type of latch was studied in considerable detail to reduce overall size of the actuator and provide highest reliability. Operating force to close the switchgear was developed in a solenoid with moving center pole piece. To prevent sliding friction, thin flexible diaphragms were proposed



...um Capsule Shown

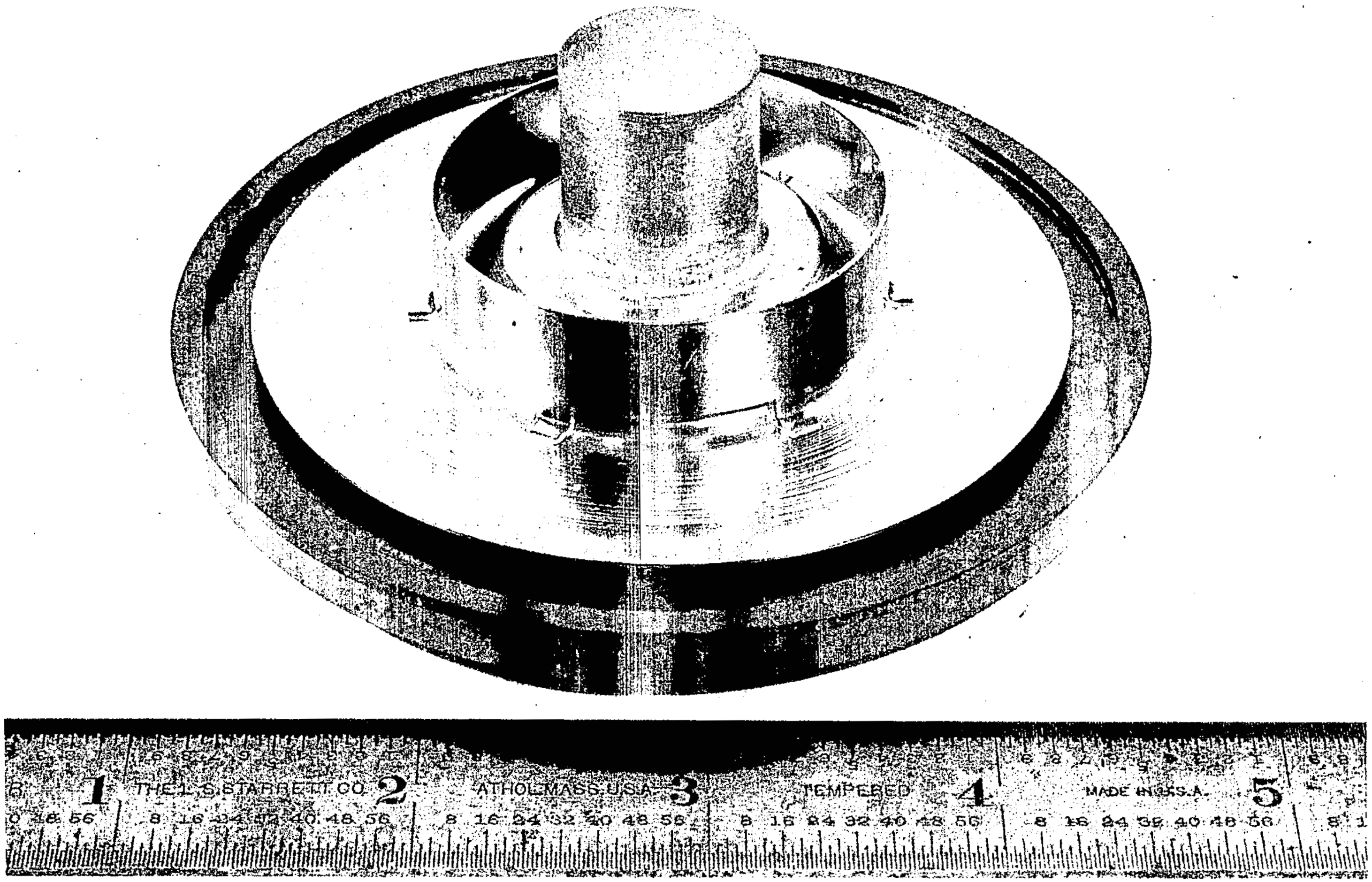
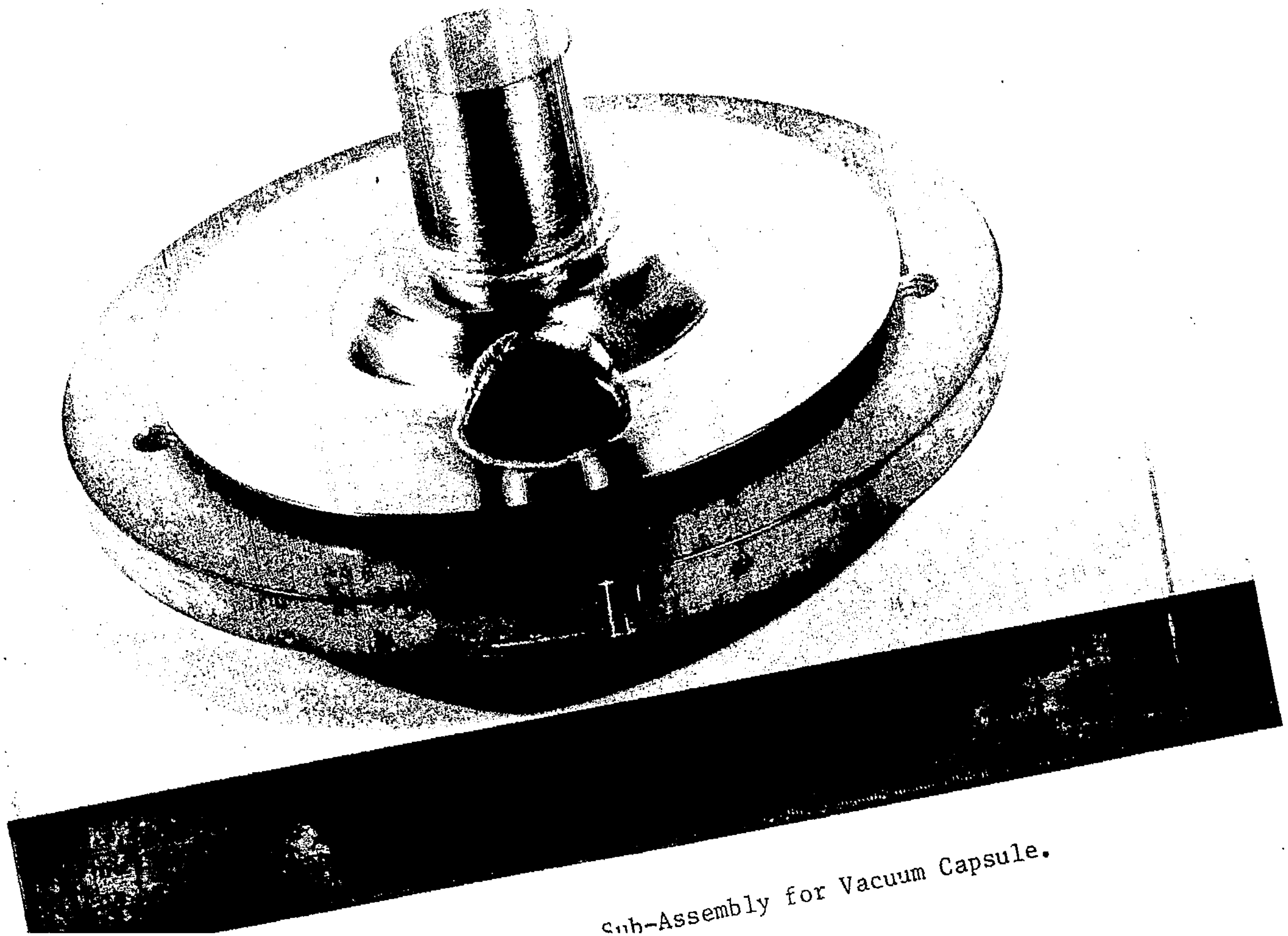


Figure 16. Upper Flange Sub-Assembly for Vacuum Capsule.



Sub-Assembly for Vacuum Capsule.

for supporting the moving parts. In order to shorten the overall mechanism, a "reverse" toggle was developed. It was arranged so the pivot of the toggle arms was not between the ends of the arms in series, but rather the arms were essentially next to each other and the pivot was above both of them.

The final actuator (mechanism) design is shown generally in Figure 18. Further detail investigation of the trip solenoid structure resulted in the design for this part of the device as shown in Figure 19. The moving pole piece which is attached to the pivot of the toggle arms is located in the trip coil magnet structure in the closed position. When the coil is energized, the pole piece is attracted to the center of the structure but at this point the toggle linkage is "over-center" and by removing the coil current the pole piece (and linkage) is free to move to the full open position. The "opening" springs provide the moving force.

In the refinement of this section of the mechanism it was also found possible to add a second coil and magnet structure which would attract the moving pole piece when energized. This arrangement was used to supplement the permanent magnet (mounted below the coil structures) and hold the toggle linkage in the closed position during mechanical tests which simulated the spacecraft launch conditions. The mechanical test series showed this additional latch was needed to pass the tests.

A major design problem involved the diaphragms which supported the main solenoid pole piece. This part had an excursion of 0.375". Considerable development work was needed to design and check out a suitable diaphragm. Initial designs gave poor operating life, and a study of the action showed the need to eliminate all possible points of tearing stress. Three thicknesses - .005, .010, and .015 inches - were checked in a special fixture on an Unholtz-Dieky vibration machine using the mechanical test specification requirements. One of two of the early diaphragms, mounted in the fixture with a center section to simulate the solenoid weight, is shown in Figure 20.

The final diaphragm design is shown in Figure 21. The sketch does not show the thin flat disks which were used on both sides of the diaphragm, in the center area, to prevent stress concentration in the ends of the slots. The best material was found to be A286 stainless steel, 0.0047" thick. The stress relieving disks were made of the same material. As a further aid to proper performance, the

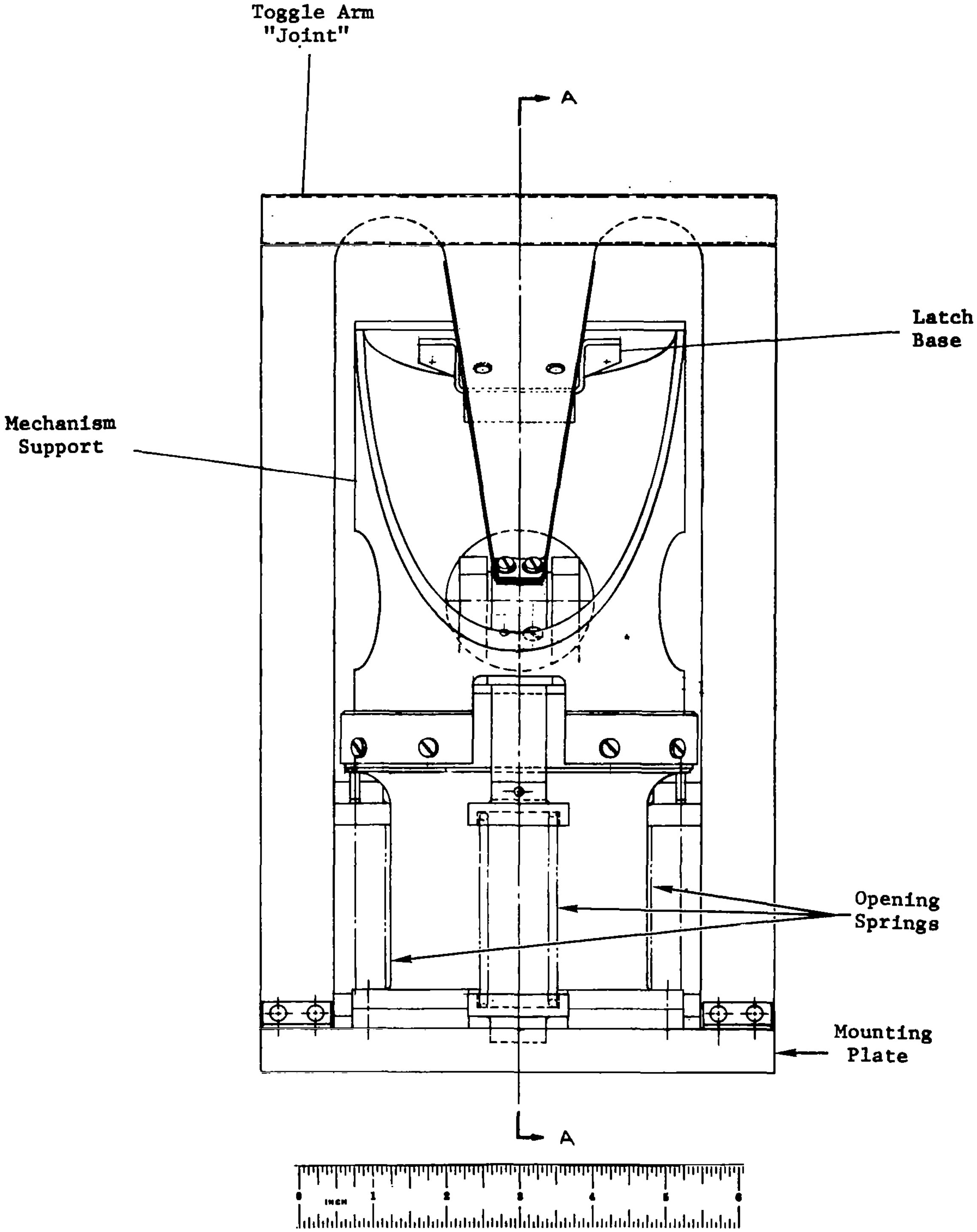


Figure 18. Sketch (Front View) of Proposed Mechanism with "Reverse" Toggle.

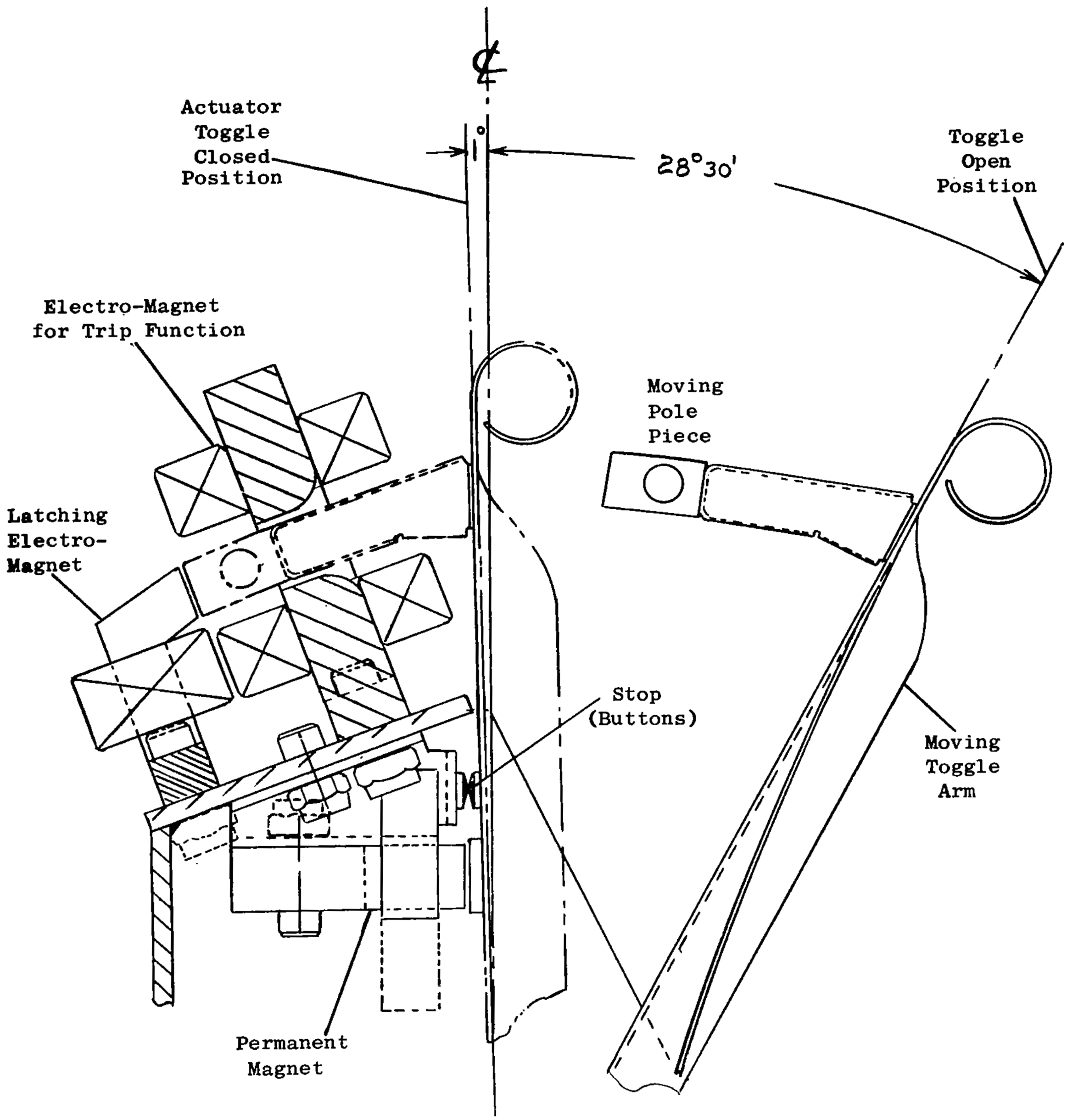


Figure 19. Sketch of Trip and Holding (Latching) Section of Proposed Mechanism (Actuator).

Figure 20. Early Sample Diaphragm for Mechanism Solenoid Mounted in Vibration Test Fixture.

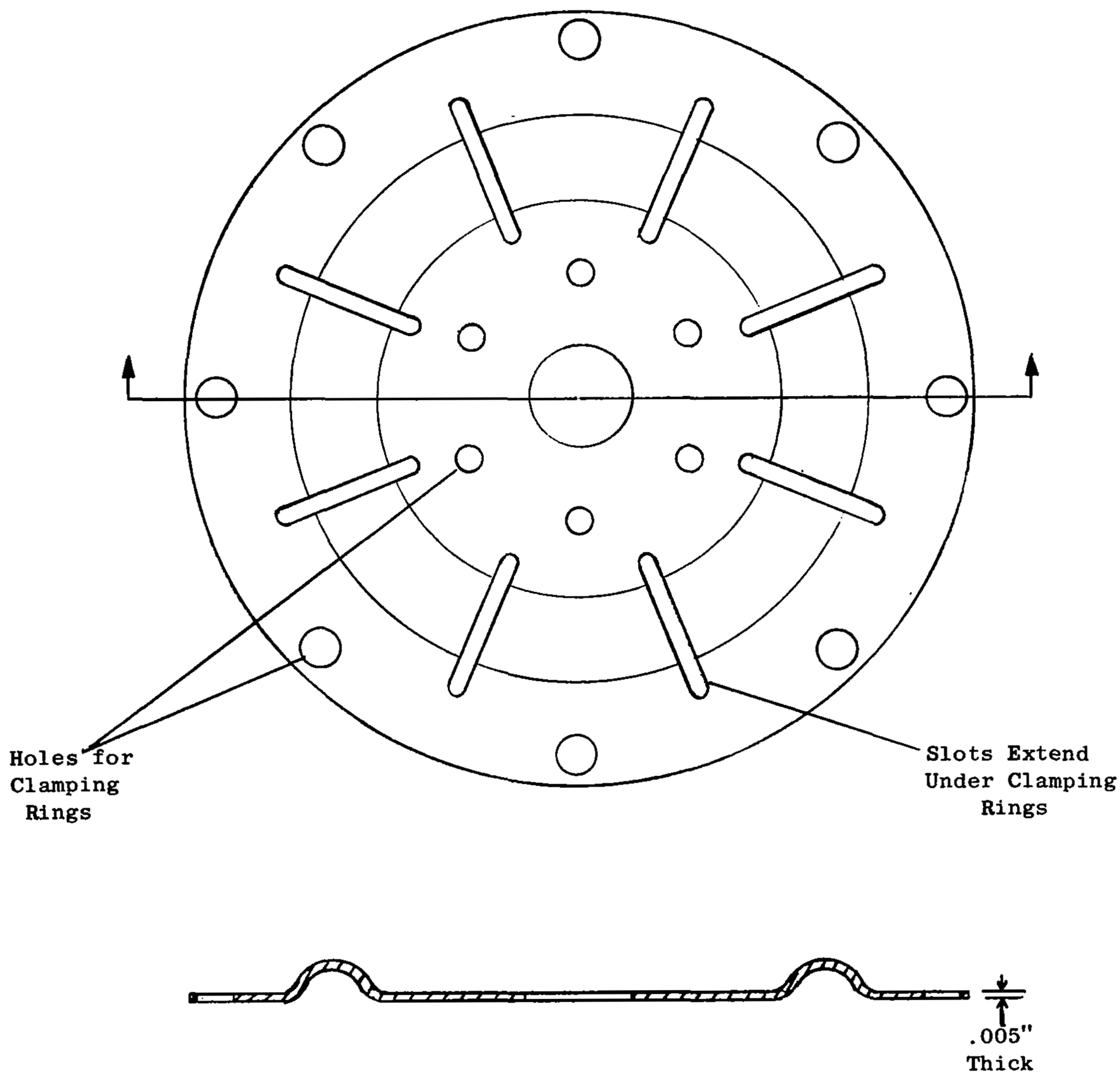


Figure 21. Sketch of Final Diaphragm Design for Mechanism.

clearance hole for the main solenoid plunger was made with a diameter which gave a maximum of 0.010" clearance. The diaphragms under maximum mechanical loading would allow this much displacement without damage.

A copy of the final mechanism layout drawing is included as Figure 22. Various details of other parts such as the flexural pivot, the assembly procedures, etc., needed solution before ordering and fabricating parts. Mating of the actuator with the AC and DC interrupter units was also necessary, and will be discussed further in later sections of this report.

The opening springs were designed to be made of Inconel-X, and #1 Temper material was used. Processing and "heat setting", as recommended in available literature, was followed by the manufacturer. Calculated stress in the spring was about 30,000 psi, which should be low enough to prevent excessive relaxation over a long time at 1100° F (593° C) maximum. Spring characteristics are shown in Figure 23. The curves of this figure, however, show a loss of spring force of about 45 percent in the case of the AC breaker, and of approximately 20 percent for the DC contactor opening springs.

A picture of the finished sample actuator is shown in Figures 24 and 25. The flexural pivot flat spring members are clearly visible in Figure 24, in the center of the devices. Figure 25 shows the actuator (mechanism) in the open position. Note that the trip coil was not installed, and neither the closing, trip, nor latch coil were installed during the initial testing. Room temperature coils were used for the mechanical check-out and testing. High temperature coils were developed and built for the interruption test series, and will be discussed in more detail in the section covering the test activity.

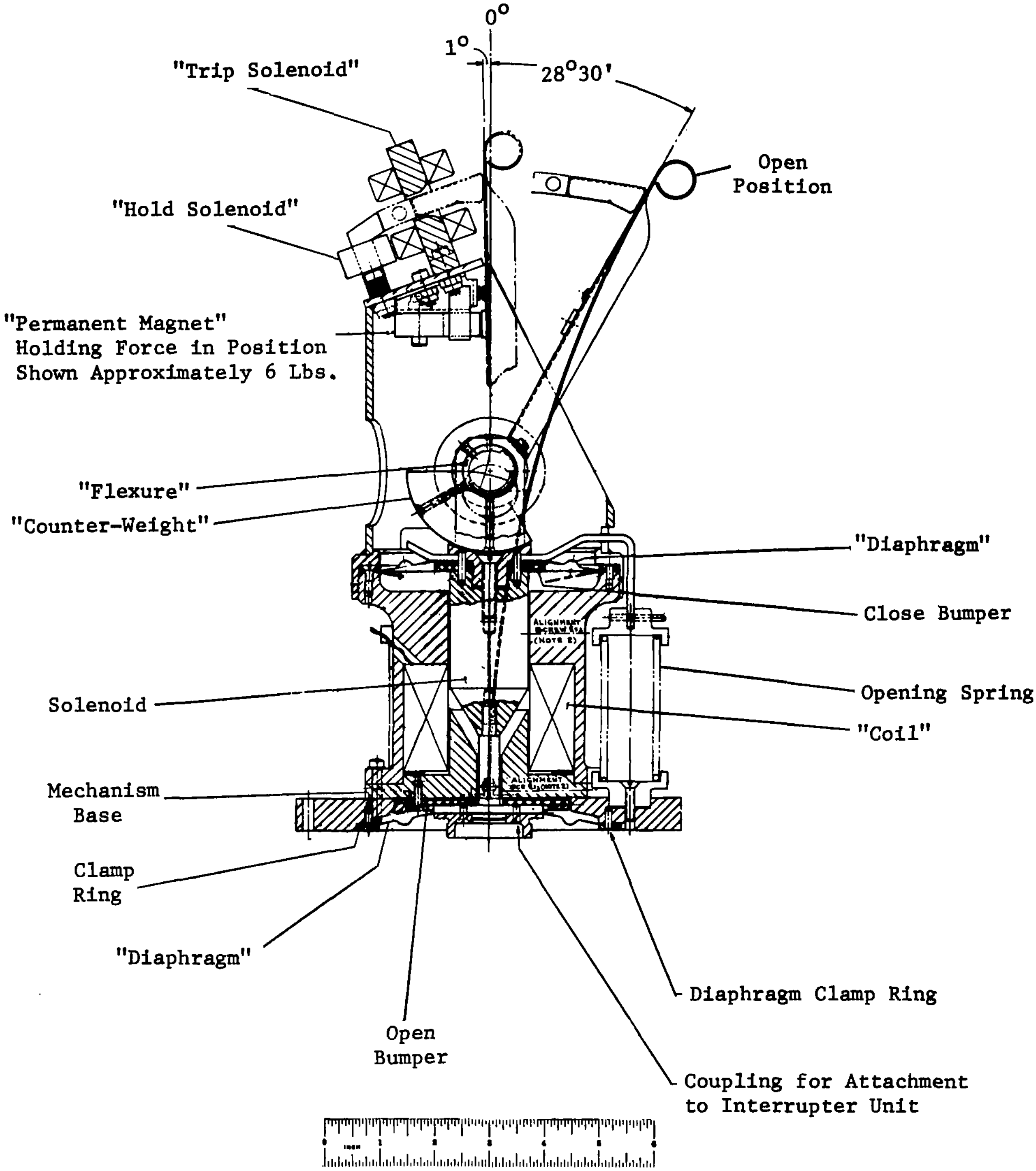


Figure 22. Layout in Detail of Operating Mechanism (Actuator) for Breaker and Contactor.

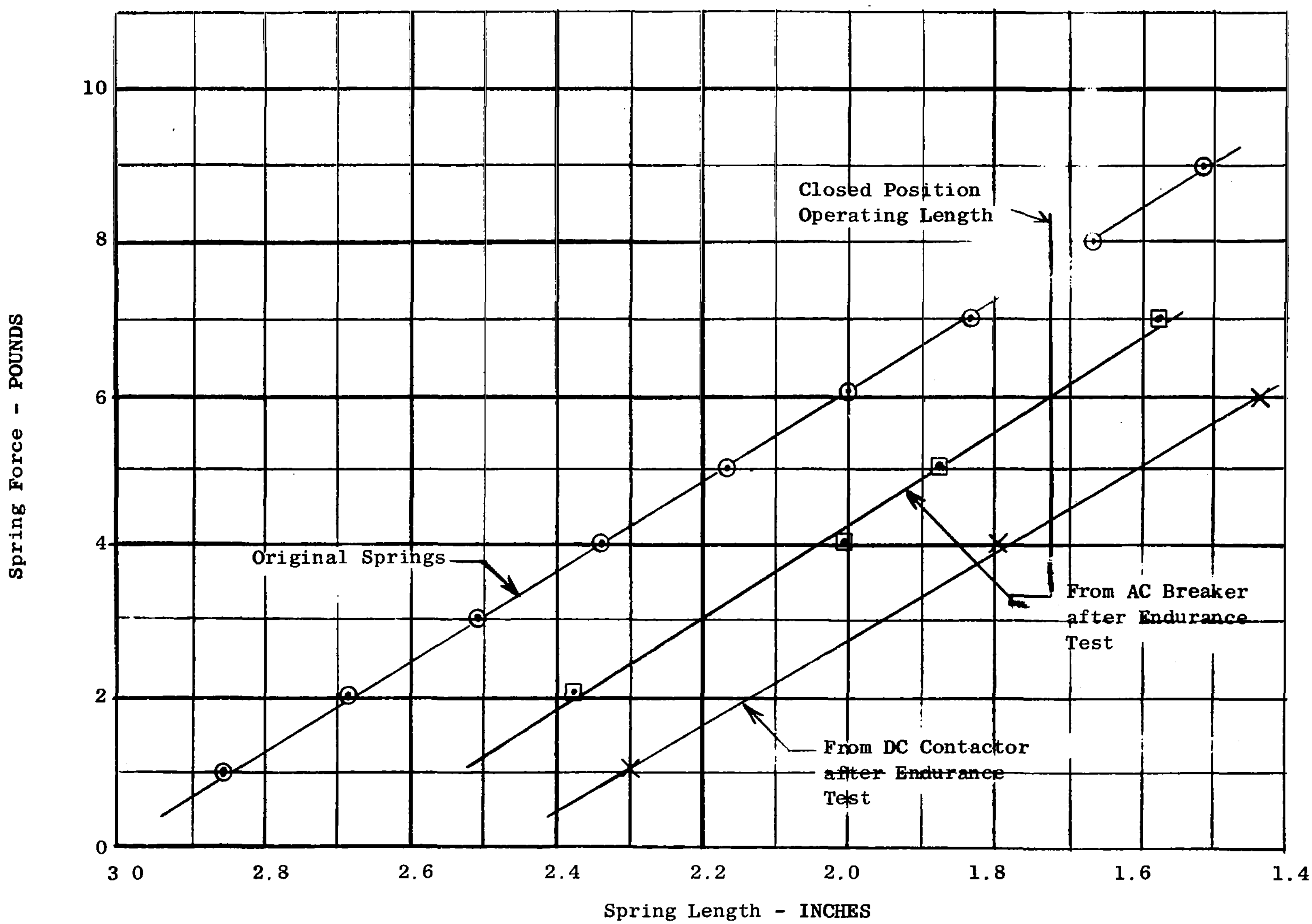


Figure 23. Actuator (Mechanism) "Opening" Spring Characteristics.

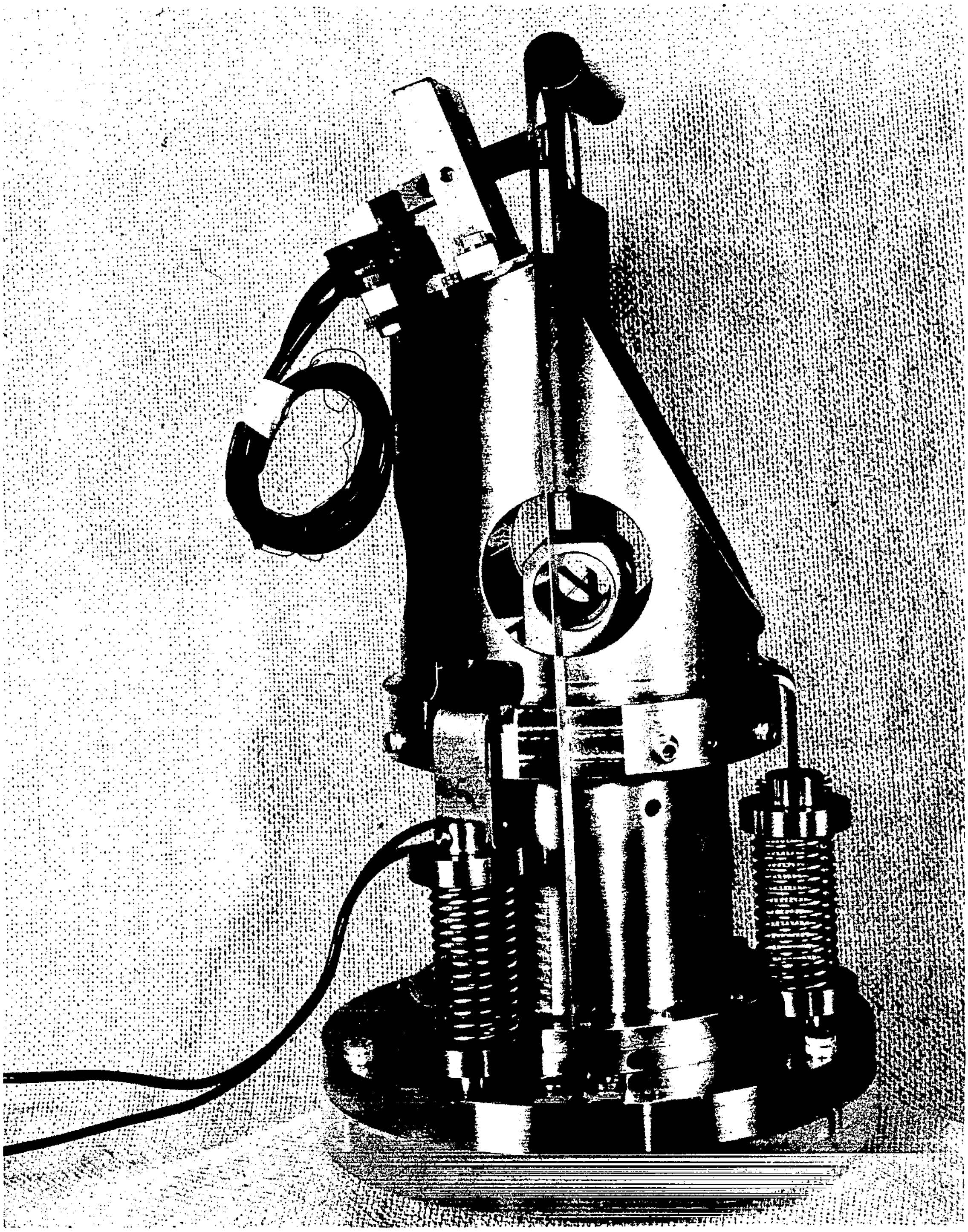


Figure 24. Actuator (Mechanism) for the Switchgear Units, Mounted on Shipping Plate.

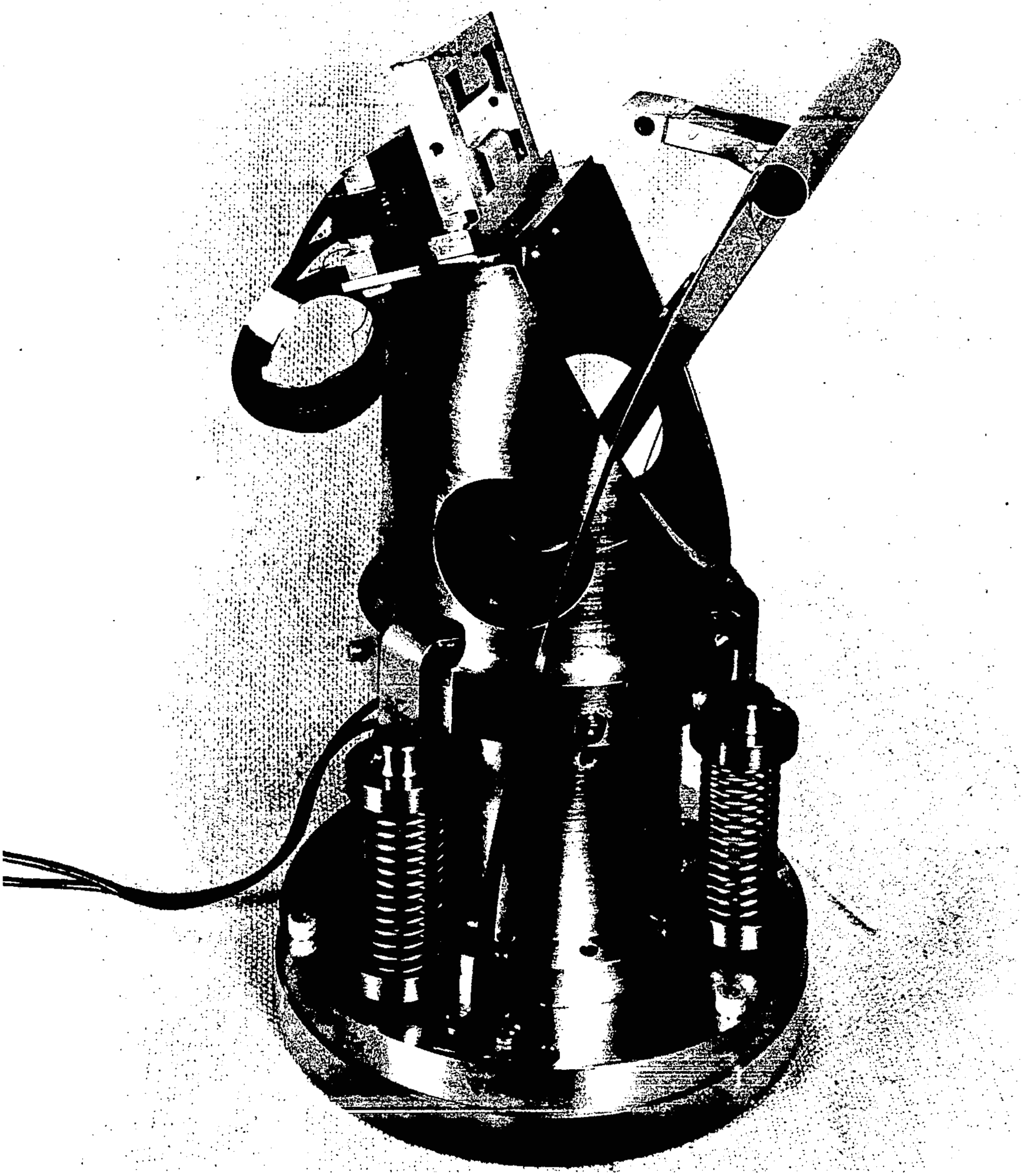


Figure 25. Actuator for Switchgear Units in the Open Position, Mounted on Shipping Plate.

IV AC BREAKER

The AC breaker, with ratings as required for use in large (1000 KVA, 3 phase) nuclear power systems, would be used as the main circuit protective breaker. The pre-flight design unit which was developed for ground testing consisted of two main sections: the Interrupter Unit and the Actuator.

Earlier sections of this report described the development of the actuator (mechanism), and the vacuum capsule which is mounted in the interrupter unit. The interrupter will now be discussed in more detail, and then the assembly to the actuator will be described, providing the complete breaker for test.

A. Design

1. General Arrangement

The final design of the interrupter unit for the breaker is shown in Figure 26. It will be noted that heat is removed from the contacts and capsule through the end flanges and the radiators which are made of Amzirc (0.15% zirconia dispersed copper). The radiators, which are cylindrical, are "heat shrunk" fitted to the flanges. The lower radiator supports the capsule.

The ion pump is attached to the pipe which connects to the capsule lower end spinning. The pump and magnet are supported by a clamp to the lower Amzirc flange.

Pressure on the contacts when the unit is closed is provided by the "wipe" spring attached to the upper flange. Between this spring assembly and the flange the copper diaphragm is clamped and this is used as the "flexible" conductor to connect between the upper terminal and the top flange and contact in the capsule. The ring to which the diaphragm is brazed (and into which the terminal is threaded) is shown on the sketch of Figure 26.

The "wipe" spring sub-assembly consists of a ceramic insulator of general cup shape, a metal split cup which has a projection under the clamping bolt washer (at top of Figure 26), with a buffer and part of the ceramic insulator

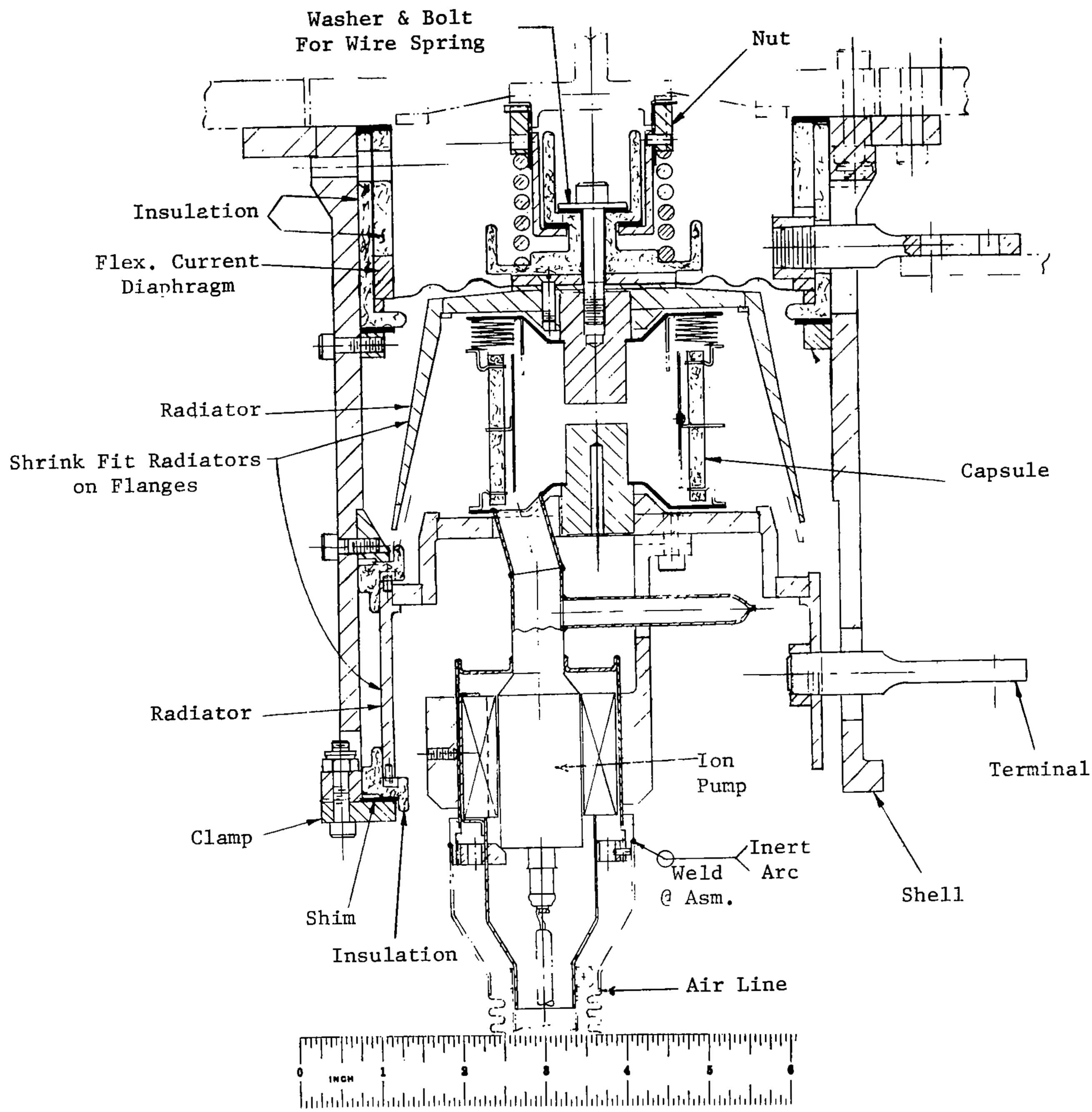


Figure 26. Layout of Vacuum Interrupter for AC Circuit Breaker.

in between. The buffer is made from "mica-mat", a sheet material consisting of mica flakes held together by an inorganic binder. The spring is held under initial compression by a threaded nut (see Figure 26) which is also used to make the attachment to the operating rod (coupling) in the actuator.

Studies of various test data covering surface creepage and withstand values with high purity ceramic, at 1000°F (538°C) and ultra-high vacuum, provided the background for the insulator designs. A minimum of 0.5" was selected for surface creepage. Data indicated this would withstand at least 10,000 volts.

The vacuum capsule with all attachments is mounted in the "shell" (refer to Figure 26) which is made of copper for good heat conductance. This shell includes a flange which is used to bolt to, and mount the breaker on, the bulkhead "heat sink". Six high purity ceramic insulators with mica-mat washers and buffers (in 2 rows of 3 insulators) support the capsules in the shell. The top diaphragm and ring are held in place by high purity ceramic cylinders, which are kept tight by a mica-mat washer above the cylinders and under the actuator flange.

2. Heat Conducting Material

Selection of a suitable material for the flanges and radiators involved a detail review of available material to select the best from an electrical and heat conduction point of view. The following tabulation lists the important properties of some of the candidate materials:

Material	Thermal Conductivity (Watts/cm²/°C) at 800°C (1472°F)	Density (gm/cu cm)	Electrical Resistivity (ohm-cm) at 1000°F	Vapor Pressure (Torr) at 1000°F	Yield Strength (psi x 10³) at 1000°F	Machinability (GE Standards)	Merit Figure for Thermal Conductivity per lb.	% Linear Thermal Expansion at 1000°F	% Linear Thermal Expansion at 1340°F
Copper	3.54	8.9	4.8	10^{-8}	--	.6	.397	.95	1.4
Copper Zirconium	3.3	8.8	6.1	10^{-8}	34	.6	.375	.96	1.6
CUBE ALLOY[1]	2.	8.7	5.5	--	42	.6	--	1.03	1.3
Tungsten	1.25	19.3	18	10^{-8}	--	.1	.065	.20	.32
Molybdenum	1.21	10.24	17	10^{-8}	30	.35	.118	.24	.4
Beryllium	.92	1.85	25	10^{-8}	--	.8	.5	.88	1.3
Stainless Steel 347	.29	7.905	110	--	19	.40	.037	1.0	1.4

[1]Not available in required forms

The first choice material was copper since it has excellent thermal and electrical conductivity. Copper loses much of its strength at high temperatures, but R.A. Wilkins and E.S. Bunn, in their book titled "Copper and Copper Base Alloys" state that copper has a tensile strength of 4,000 psi even at 700°C (1292°F). This was sufficient strength for the outer shell which had a maximum calculated temperature of 1122°F, and possibly for the radiator fins with a maximum calculated temperature of about 1227°F. However, the temperature of the flanges on the vacuum capsule were above 1250°F, which made the use of copper marginal in these parts.

CUBE-ALLOY, a dispersion hardened high conductivity copper base material, was investigated because of its relatively high strength at high temperature, but this promising material was found to be available only in wire, or up to 1/2" diameter rod, and thus not suitable for the radiators.

A third material with good thermal and electrical properties is copper-zirconium. This material retains appreciable strength even at the high capsule temperatures. The strength of this material is obtained by alloying a small percentage (0.15) of zirconium with copper, into a precipitation hardened material. Over long time periods at high temperatures it is reported that the zirconium will go back into solution and be no stronger than copper. Information from American Metal Climax, Inc., maker of the material known as AMZIRC, indicates however that sufficient zirconium will be left in the grain boundaries to accomplish the strengthening function for the Switchgear Program. While specific data were not available above 1275°F, the following typical information has been made available.

At 1100°F a 17% cold worked specimen took 100,000 hours to creep 1% at 1,000 psi. At 1200°F the data for various amounts of cold work indicated:

Cold Work %	Ultimate Tensile psi	.1% Yield psi	Elongation %
None	8,500	4,700	8
5	10,500	8,500	7
20	15,000	13,000	4
40	18,700	16,500	4

Based on this data, the copper-zirconium was selected for the flanges of the vacuum capsule, while copper was used for the interrupter outer shell. Copper was also used for the upper radiation fin, but copper-zirconium was required for the lower fin since it supports the vacuum capsule and the added strength is important.

The needed heat transfer by radiation to the shell was obtained by coating both the radiator and shell surfaces with an iron titanate coating. This coating applied by a plasma torch spray, was originally used for heat transfer surfaces of space radiators. It provides an emissivity of 0.85 or better, and tests indicate it will hold up well in the temperature and vacuum environment specified for the switchgear. The shell and two radiators for one breaker unit, after the iron titanate coating was applied, are shown in Figure 27.

B. Assembly

The initial assembly work involved the build up of the vacuum capsule and interrupter unit. With the capsule baked out and sealed off and ion pump attached, the necessary cooling line and heat shielding was installed. Then the iron titanate coated radiators were "heat shrunk" to the capsule flanges. Thermocouple leads that were used to measure the temperatures in various locations were also attached.

The capsule with its attachments was then mounted in the outer shell, and the clamps with spacers made of "mica-mat" were tightened to hold it in place. The copper current-carrying diaphragm was next put in place above the capsule, the retaining washer attached, and finally the "wipe" spring assembly was attached using the stainless steel bolt (refer to Figure 26). Of course, all copper parts were bright cleaned before this assembly work. The wipe spring, made of #1 Temper Inconel-X was designed to provide 50 pounds of contact pressure in the closed position. The force-deflection characteristics are shown in

Figure 28. A loss of about 20 percent in operating spring force indicates that the spring should be improved.

Special flat wrenches were used to hold the "wipe" spring nut and to turn the threaded coupling part of the actuator, as it was assembled to the interrupter unit. The amount of threaded engagement determined the deflection of the wipe spring and contact gap spring. A layout of the completely assembled breaker is shown in Figure 29.

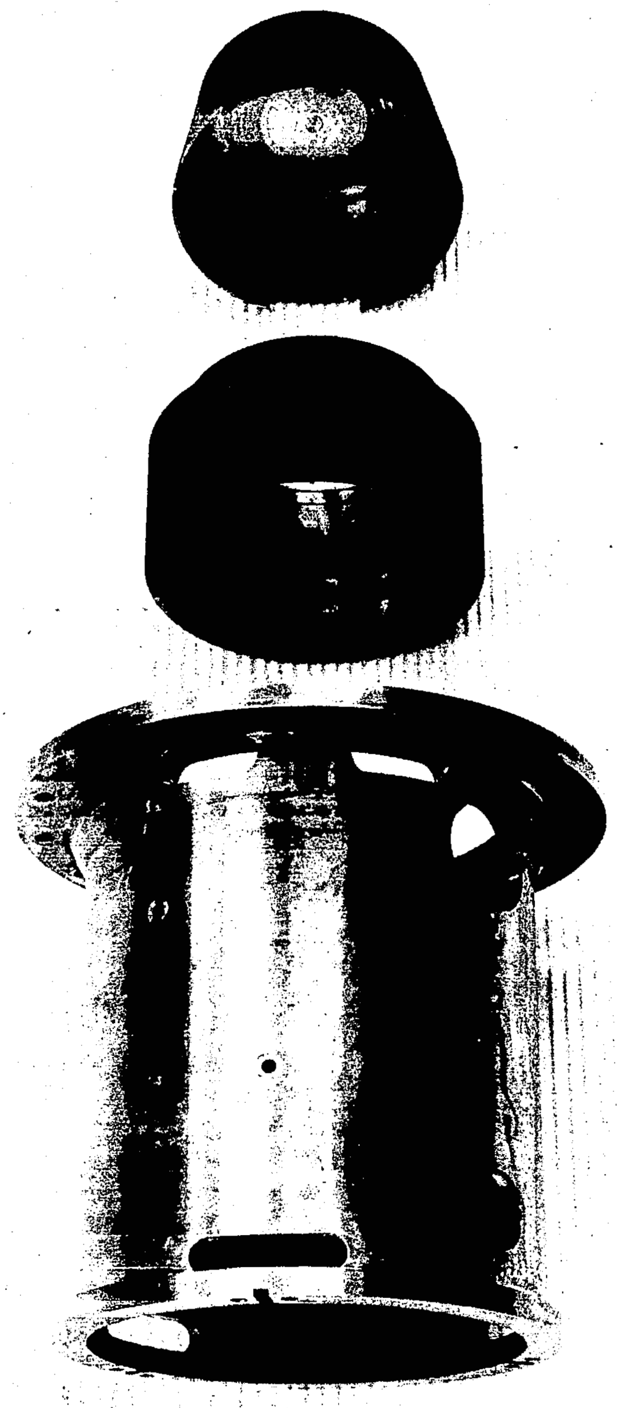


Figure 27. Outer Shell Along with Upper and Lower Radiator After Iron Titanate Plasma Spray Coating.

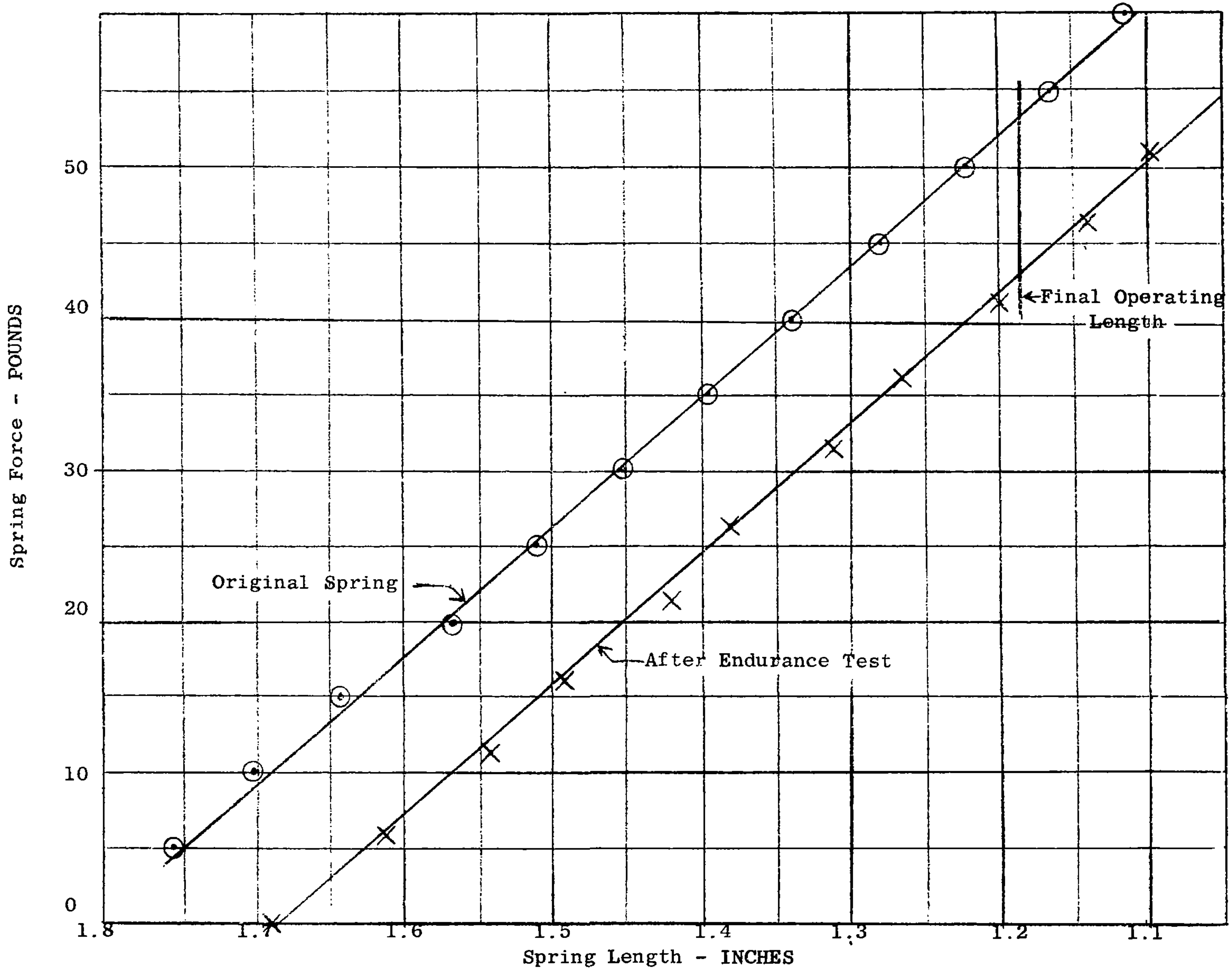


Figure 28. AC Circuit Breaker Contact "Wipe" Spring Characteristic, Before and After Endurance Test (1000 hours at 1100°F).

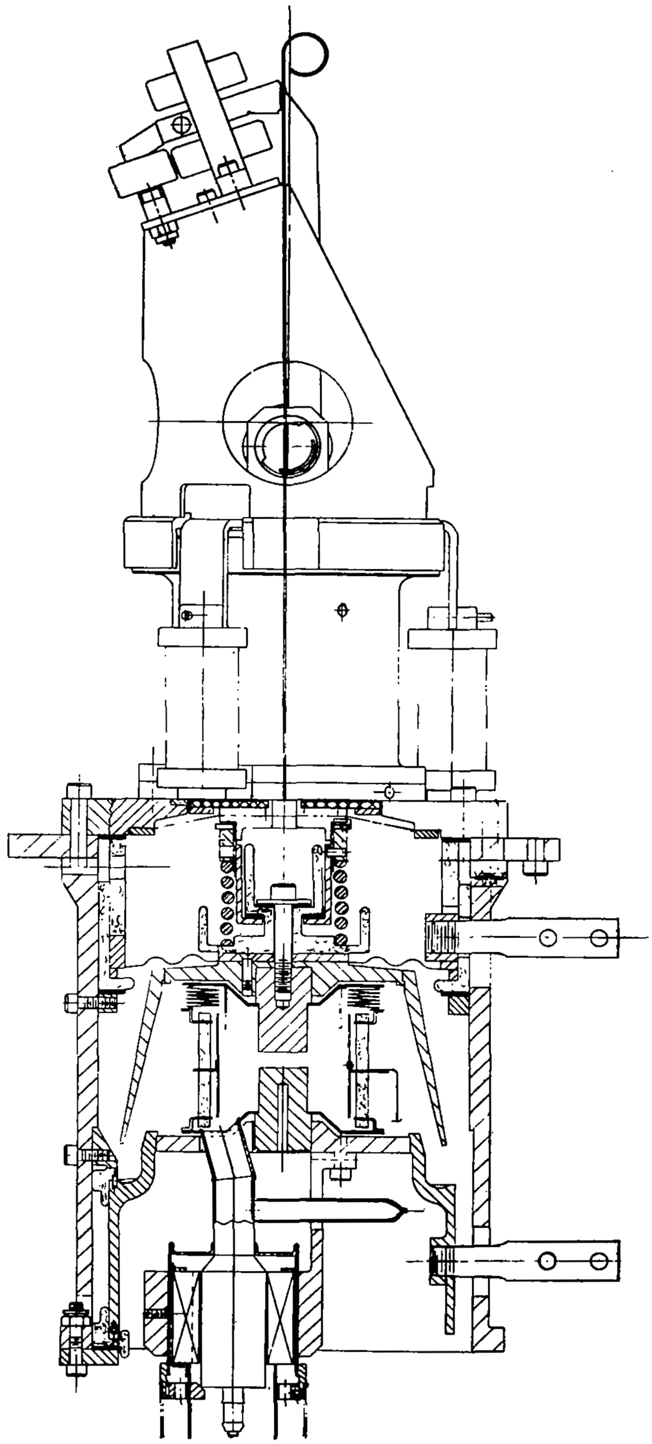


Figure 29. Layout of AC Circuit Breaker, Showing Actuator (Mechanism) Attached to Interrupter Unit.

V. DC CONTACTOR

The DC contactor, which is expected to be used for switching the power supply to large ion engines, is rated 10 KV. The continuous and interrupting current was 10 amperes, which meant that the capacity of this device was considerably below that of the breaker. However, the design was developed to use as many parts of the breaker as possible. The interrupter design will be described in detail, along with assembly of the complete contactor for test.

A. Design

The final design of the DC interrupter unit is shown in the copy of the layout in Figure 30. It will be noted that the capsule design is the same as was used for the AC breaker (see Figure 26). However, there are no radiators needed because of the lower current rating and contact heating. The outer shell is smaller and is made of nickel, but the insulation creepage distances are double the length of the AC breaker.

Studies of data developed in the Research & Development Center of the General Electric Company indicated that the clean, high purity alumina ceramic insulator surface withstand value at $1000^{\circ}F$ and 10^{-6} (or lower) torr pressure and 0.75" distance between electrodes would be at least 20,000 volts, with minimum conditioning. W.T. Starr (R&DC) has shown that with proper surface cleaning and conditioning, and rounded electrode surfaces, a 0.25" distance would withstand as much as 80 KV.

In designing the contactor no attempt was made to provide optimum electrode surfaces because of the many points where live parts are touching the ceramic. Therefore a compromise was made and the minimum length of 0.75" was selected for all creepage distances, with the expectation that the desired withstand value would be easily obtained.

The current carrying diaphragm for the moving contact connection was similar to the one for the AC breaker except that thinner material was used. The capsule is supported in the shell by a split ring support (Figure 30) which also carries current to the lower terminal. The "wipe" spring assembly is similar to the

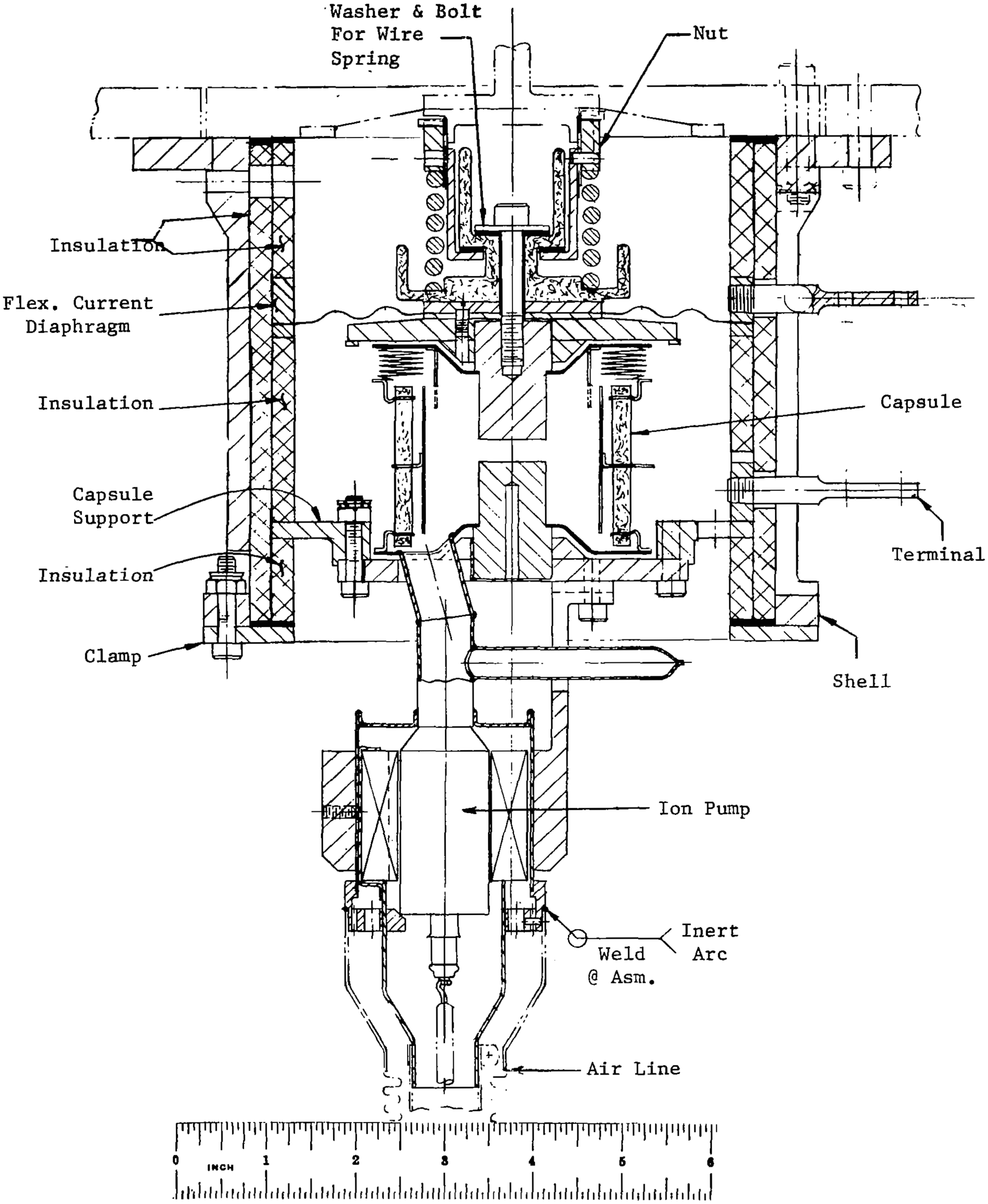


Figure 30. Layout of Vacuum Interrupter for DC Contactor.

breaker assembly except that a different spring is used to provide approximately 20 pounds contact pressure when the contactor is fully closed. The spring. made of #1 Temper Inconel-X had the characteristics shown by the curve in Figure 31. As in the case of the AC wipe spring and the opening springs the loss in spring force at the working length indicates that an improvement in this part should be made.

B. Assembly

The vacuum capsule, with attached ion pump, sealed off after bake-out and evacuation, was attached to the lower support plate (which also is used for current carrying and terminal connection. This sub-assembly was placed in the interrupter shell along with the required ceramic cylinders, and the bottom ring attached to the shell to hold the parts in place.

From the top of the shell, the remaining ceramic insulating cylinders were installed, and then the copper current-carrying diaphragm was put in above the capsule. After attaching the copper disc, the "wipe" spring assembly was fastened to the capsule by the center bolt, the upper terminal was then inserted into the diaphragm outer ring. Figure 32 shows the assembled contactor interrupter unit.

Special flat wrenches were used to hold the "wipe" spring nut and to turn the threaded coupling part of the actuator, as it was assembled to the interrupter unit. The amount of threaded engagement was used to provide the required 1/8" of spring compression after the contacts closed. The overall assembled unit is similar to the breaker shown in Figure 29, except for the interrupter (lower) section.

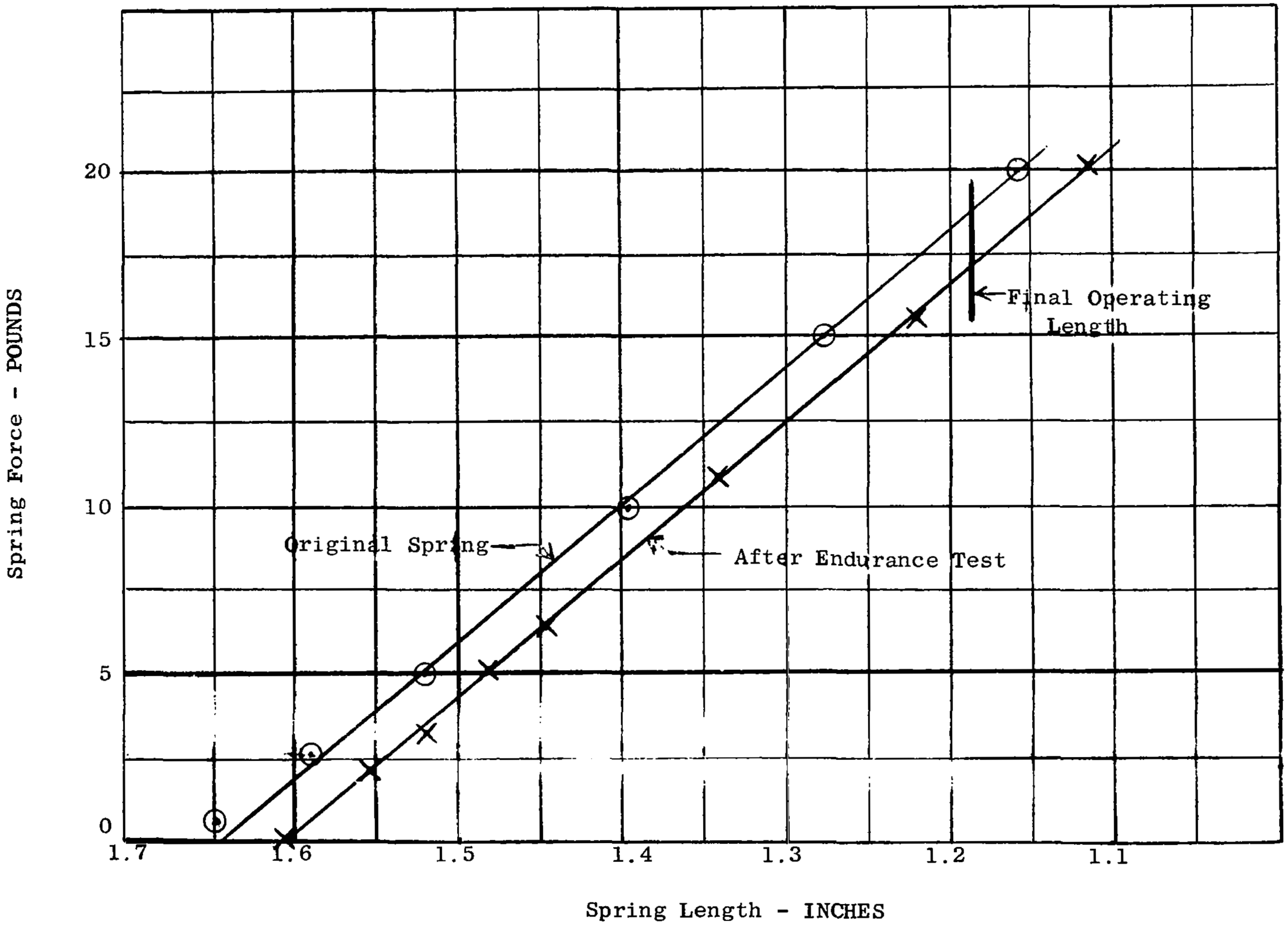


Figure 31. DC Engine Contactor Contact "Wipe" Spring Characteristic, Before and After Endurance Test (1000 hours at 1100°F).

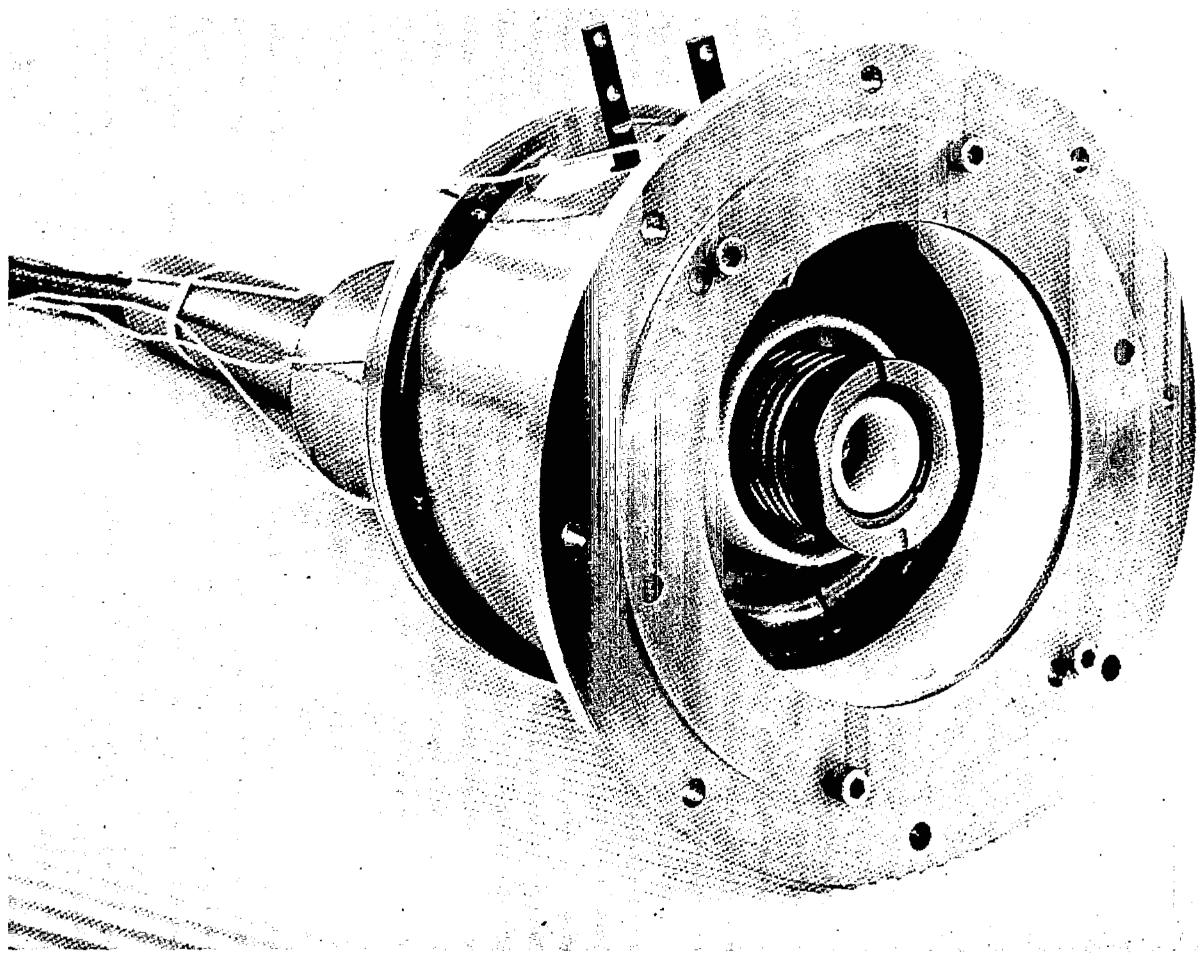


Figure 32. DC Interrupter Unit, Viewed from the Actuator End Showing the Electrical Diaphragm and "Wipe" Spring Assembly.

VI. TEST PROGRAM AND RESULTS

A major part of the development effort on this program involved the testing activity. The requirements were established so the test data would demonstrate performance of the switchgear when carrying the continuous current over a long period of time, would determine interrupting ability, and indicate any problems from expected launch mechanical conditions. All electrical tests were to be made in a $1000^{\circ}F$ ($538^{\circ}C$) high vacuum environment.

This section of the report will describe the test requirements in detail, discuss the preparation of the test facilities, and provide a summary report of all test results.

A. Test Specifications

The testing program on this contract required that the following tests be performed:

1. Heat Run. In $1000^{\circ}F$ ($538^{\circ}C$) and 10^{-6} torr (or lower) pressure, determine temperature rise with breaker carrying 600 amp rms., 1000 to 3000 cps, and with contactor carrying 10 amp DC.

2. High Potential. Determine leakage current under same environmental conditions as for the heat run, with 1500 V rms, 2000 cps across capsule (center-shield to end terminal) of AC breaker, and 15,000 V DC across same points of DC contactor.

3. 1000 Hour Endurance. Measure temperature rise, and any change in opening force, at end of 1000 hours in the high temperature, low pressure environments (see 1 above) with normal full load current flowing continuously in the switchgear units.

4. Mechanical Test. Perform vibration, shock, acceleration, and acoustic noise tests on the samples after other tests are completed.

5. Interruption Test. Install high temperature operating coils, and in the high temperature, high vacuum environment, determine interrupting performance at full voltage and twice normal current for both the AC breaker and DC contactor.

The above requirements were the basis for detail planning for the various tests. Information concerning the set-up and procedures for the tests is included in Appendix D.

The results of the tests will be reviewed and detail results reported in the subsequent appropriate parts (C through G) of this Section VI.

B. Facilities

All the tests at high temperature and vacuum were made in a Varian Ultra-High Vacuum 24" diameter metal bell-jar system having a 1000 liter/second ion pump. This pump is used after the tank pressure is reduced to a few microns with sorbtion and mechanical pump roughing systems. The equipment is shown in Figure 33.

1. Oven

To provide the high temperature, a special oven was developed and built. Figure 34 shows the layout of the special oven. It was made from vacuum melted Rodar (an Fe, Ni, Co alloy). This material was selected on the basis of the low outgassing rate shown by the earlier capsule material tests.

The oven was designed to use long quartz tube lamps for heating the slat surfaces. Behind the lamps, 3 layers of .003" Rodar separated by .010" dia. wire, were used to reduce heat radiation to the tank walls. The various parts of the oven were fastened together using the inert gas welding technique.

A total of 21 lamps are used around the oven sides, controlled in three sections by separate Variacs (variable transformers). The group of top lamps and bottom lamps are controlled by an additional pair of Variacs. Total connected lamp load is about 10,000 watts, and was more than enough to obtain complete and steady temperature control when the samples were at 1000°F and the vacuum tank side walls were being water cooled. The oven in the fully assembled condition is shown in Figure 35, before the vacuum tank cover (top) was put in place.

2. Power for Testing

Two types of power were required for the test program. First, the continuous current for the heat run and endurance test (10 amp DC and 600 amp 2000 cps). Second, the high voltage and twice normal current for the close-open power

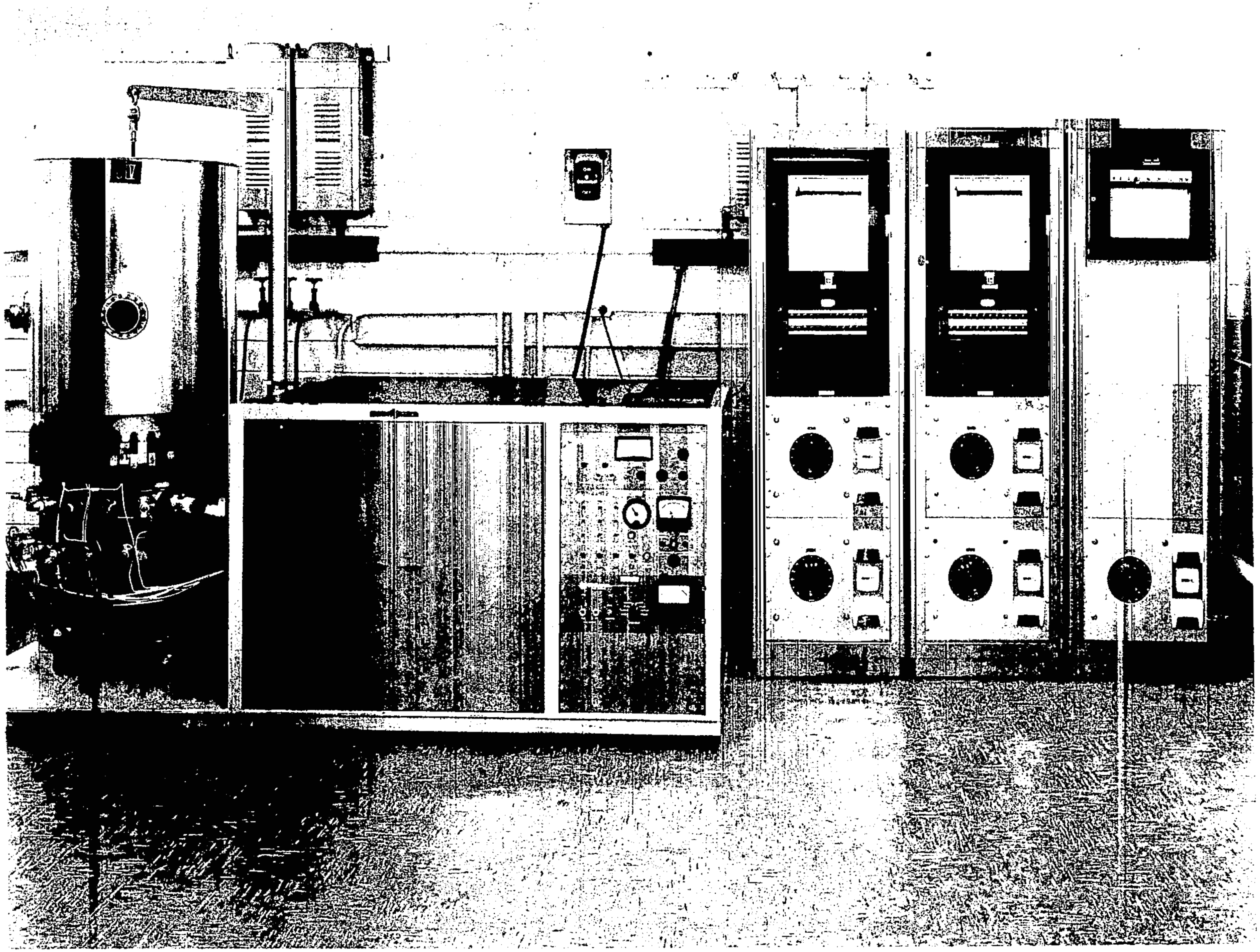


Figure 33. Overall View of Ultra-High Vacuum Chamber Ion Pump, Automatic Temperature Recorders, and Oven Controls Used for All High Temperature Testing.

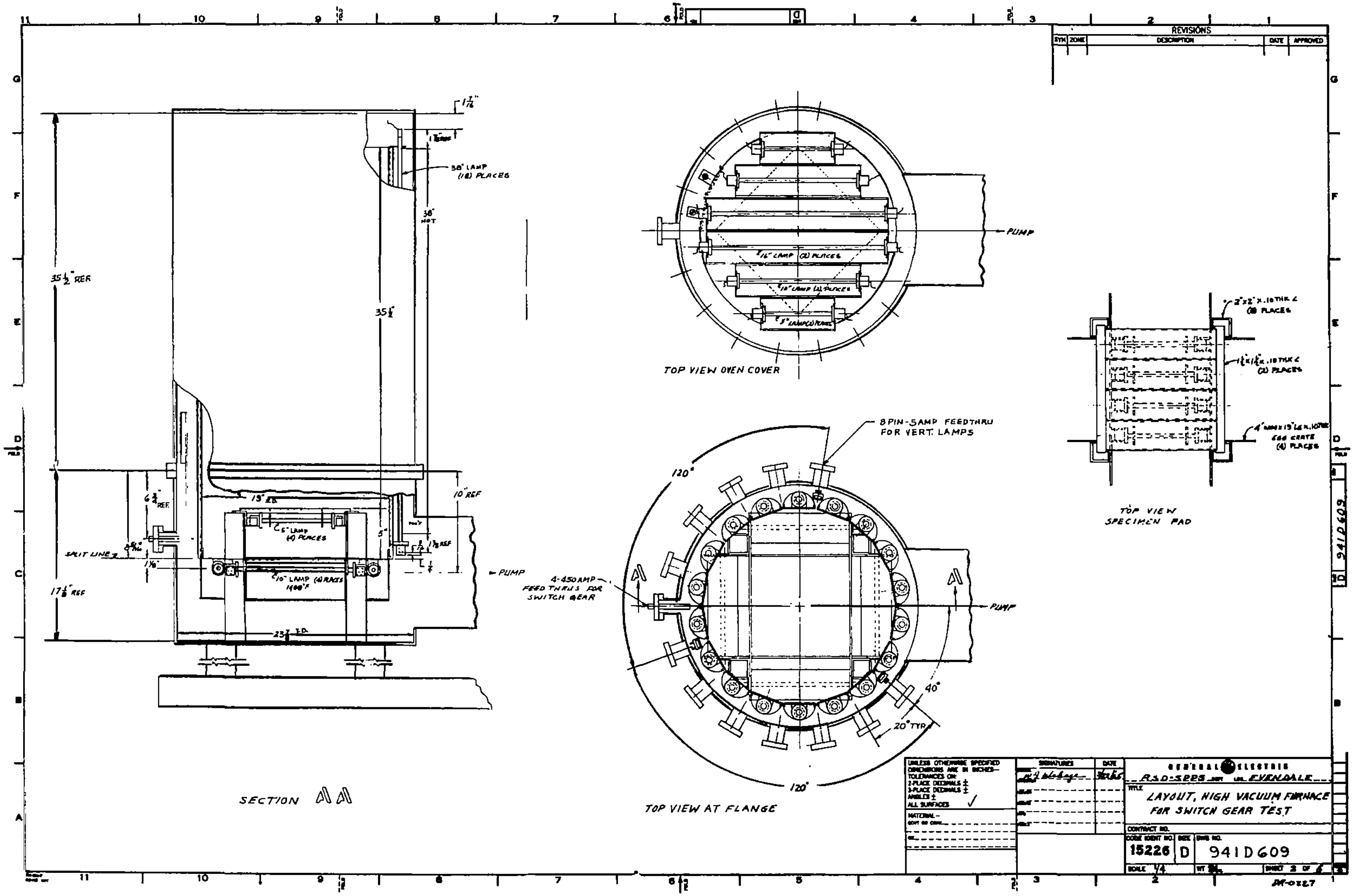


Figure 34. Layout of Radiant Heated Oven for High Temperature Tests in Vacuum Tank.

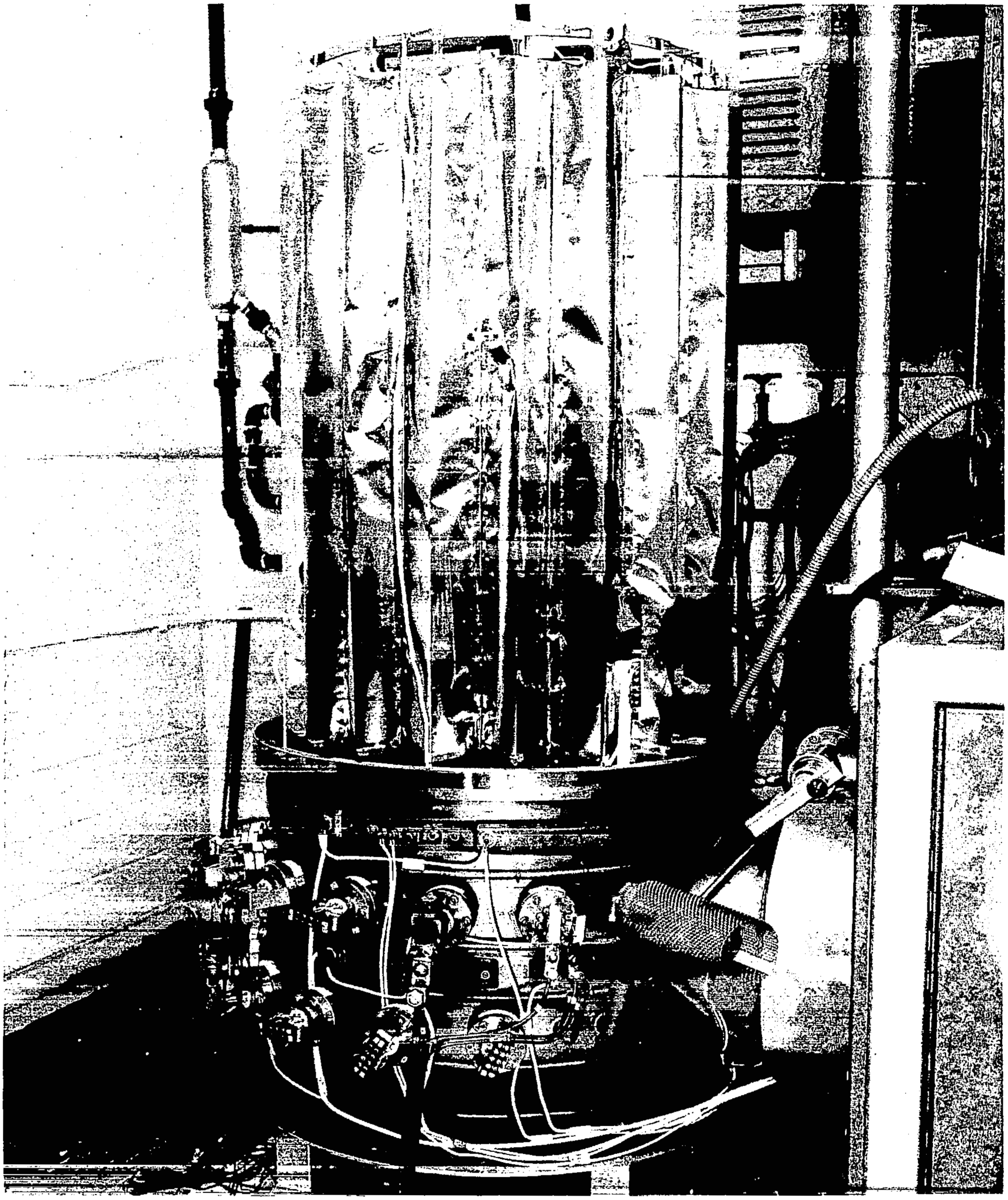


Figure 35. Switchgear High Temperature Test Oven in Position in the C IV Vacuum Tank Base, Prior to Installing Tank Lid (Cover).

interruption tests. Both of these supplies will be described in the following paragraphs.

The 10 amp DC continuous current was furnished from a rectifier circuit, with calibrated and level controlled output.

The 2000 cps, 600 amp power was furnished from a 7 KW, adjustable frequency power amplifier, through a 115 to 6 volt, 600 amp high frequency transformer. The unit was satisfactory for a range of 1000 to 3000 cps, and was able to be operated at a maximum of 150 V input, to handle the increased drop that occurred in the switchgear at high temperature.

The power supply for the interruptior tests was considerably more involved than for the continuous current supply, and the problem was handled with two different circuits.

DC Test Power

The DC power was obtained from a high voltage, high "Q" capacitor bank which was discharged (when the sample contactor was closed) through a non-inductive 1000 ohm resistor. Thus, with a 10 KV charge on the capacitor the discharge current (initial) was 10 amperes. Selection of the capacitor bank size and maximum charging voltage was based on the length of time the contactor would be closed. Details of the 10 KV test circuit are shown in the upper part of the schematic diagram, Figure 36.

Provision was made for charging the capacitor bank with the contactor open and the normally closed grounding switch energized and in the open position. When the proper voltage was reached and the charging current was zero, the contactor was operated to make the test. A non-inductive, shielded, shunt (0.048 ohms resistance) measured the current. The voltage at the terminals (tank feed-throughs) was measured by a non-inductive resistance voltage divider with a value of 100 megohms to 500 ohms. A maximum of 350 μf from 8-175 μf, 6 KV capacitors connected in series/parallel, was available, having a total of 24,800 joules at a charging voltage of 12 KV.

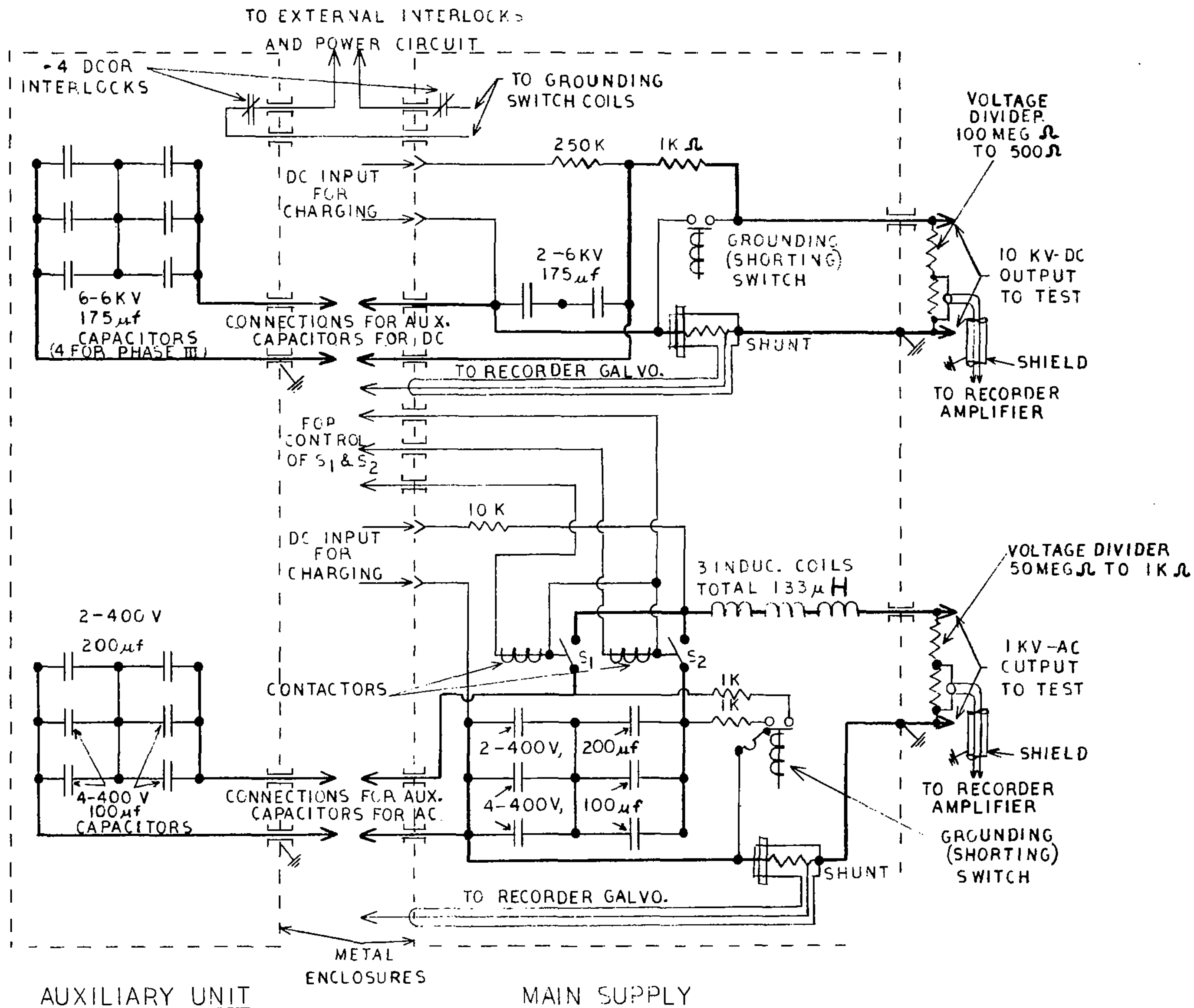


Figure 36. Schematic Diagram of Test Power Supply.

All control of the capacitor charging and contactor operation was centralized in one cabinet, having the circuits shown on the schematic diagram in Figure 37. The circuit will be discussed in more detail under the AC test power supply description.

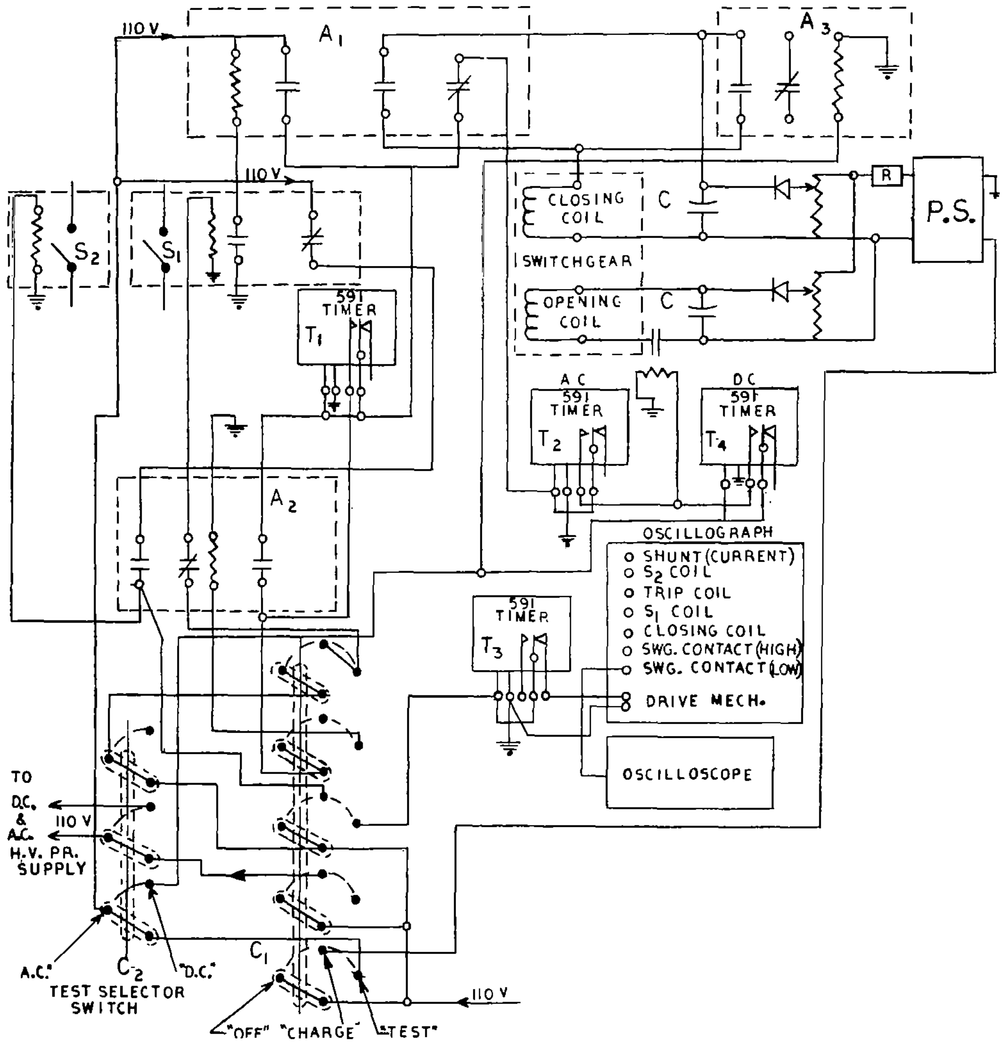
AC Test Power

The AC tests were planned to use a "synthetic" circuit for the interruption power. The basic power circuit is shown in the lower part of the schematic in Figure 36. All control circuitry is shown in the diagram of Figure 37. The basic test circuit utilized "ringing" circuits, having two high "Q" capacitor banks and one common inductance coil. Contactors were used to connect one capacitor bank in the circuit for the closing breaker test, and the other bank for the opening test. Close timing of all components is essential in order to draw power from the capacitors for a minimum time (and thus have minimum bank discharge).

The circuit inductance was provided by a set of 3 special flat foil inductance coils, each having a value of about 30 microhenry. By proper spacing and turn direction, a range of values could be obtained. Furthermore, each capacitor bank consisted of 6 high "Q" units, having a normal rating of 400 volts, connected in a series/parallel configuration to provide a range of 60 to 190 microfarad. The capacitor insulation level was adequate for operating up to 800 V, giving a total charging value of 1600 volts and providing initial rms on circuit "make" of about 1100 volts. The calculated values for the "ringing" circuit frequencies is shown below:

Frequency	- cps	1000	1500	2000	2500	3000
Capacitance	- μf	191.0	127.3	95.5	76.4	63.7
Inductance	- μH	132.6	88.4	66.3	53.0	44.2

The coil design was recognized as especially critical, and based on limited available reference data, a "Brooks" type coil made of Litz wire was considered. In such a coil, the section through the conductors would be square, with each dimension equal to the coil radius. However, the Litz wire was not readily available and was expensive, so the foil type conductor design was used. The final coil consisted of 8 turns of a conductor made up of 10 layers of 5" wide,



A-1 AUXILIARY RELAY — 2 N.O., I NC
A-2 AUXILIARY RELAY — 2 N.O., I NC
A-3 AUXILIARY RELAY — I N.O., I NC
C-1 3 POSITION CONTROL SWITCH — "OFF" - "CHARGE" - "TEST"
C-2 2 POSITION TEST SELECTOR SWITCH — "A.C." - "D.C."
P.S. — POWER SUPPLY FOR SWGR. OPER. COIL CAPACITORS
S_1, S_2 — MAIN SWITCH (CONTACTOR) FOR POWER CAPACITORS
T-1,2,3,4 ELECTRONIC TIMERS

REFER TO SCHEMATIC DIAGRAM 142B1572 FOR POWER SUPPLY CABINET

Figure 37. Schematic Diagram of Control for Test Power Supply and Interruption Tests.

0.020" thick copper, with insulation between layers, and a transposition of the 10 layers in the center of the conductor length, to reduce losses and skin effect at the high frequencies.

The final coil had an inside diameter of 13-3/4", and an outside diameter of 18-1/4". The actual inductance value checked very close to the calculated amount. However, as was recognized initially, the flat conductor coil might be subjected to "fringing" flux and eddy current losses but it was expected to be of low value. Unfortunately, this was not the case, and the high eddy currents caused the "Q" of the "ringing" circuit during the AC test to be limited to about 15. This was much too low for the slow speed of the breaker operating mechanism. Thus, as is noted in Section VII, new coils will be needed to provide a better test circuit, along with a new mechanism to give more consistent and higher speed operation.

Test Control Circuit

The control circuit, shown in Figure 37, includes two selector switches. C_2 is used to set up for either the AC or DC test, and C_1 to provide a "charge" operation, and then the test sequence. With C_2 in the DC position, turning C_1 to "charge" opens the DC capacitor shorting switch, and closes the charging circuit. When the capacitors are at the proper voltage, C_1 is turned to "test". This energizes A-3 to close the contactor, and starts timer T-4 which closes the trip coil circuit after a predetermined time delay.

The control sequence for an AC test is more involved. Selector switch C_2 is placed in the "AC" position. Then when C_1 is turned to "charge", the capacitor bank shorting switch is opened, S_1 and S_2 are closed, and the DC supply will charge the capacitor banks. Control switch C_1 is then turned to "test" which initiates the entire testing sequence, as follows:

1. S_2 opens (S_1 stays closed) and A_1 closes, energizing breaker closing coil, and starting timer T_1.
2. When T_1 times out, S_1 and A_1 open, A_2 and S_2 closes, and breaker trip coil is energized.
3. Timer T_3 is used to limit the operating time of the oscillograph to save paper, and closes after T-2 times out.

Interrupting Test Power Cabinets

Two cabinets were built to hold the capacitors, coils, switches, shunts, etc., along with needed control leads and the high current bus. One cabinet is the "main" unit and is shown in Figures 38 and 39. The other cabinet is similar, but contains only the extra capacitors and necessary bus work. Insulating panels are used near the coils, and for supporting the resistors, switches, and all terminal connections. The coils can be moved on the wood supports for inductance adjustment. The AC test capacitor adjustable bus connections are visible below the switches S_1 and S_2 in Figure 38.

C. Heat Run Test

For the heat run test the units were mounted in the test tank as shown by the layout sketch, Figure 40, and described in Appendix D. Note especially the low inductance 600 amp bus, the ion pump air lines, and the location of the switchgear samples in relation to the oven lamps.

Important temperatures of points on the oven and the samples were measured with a total of 48 thermocouples. Their locations are shown in the sketches of Figures 41, 42, and 43, which also indicate the thermocouple reference numbers. The thermocouples were made of platinum-platinum 10% rhodium and connected to two automatic recorders. Special chromel-alumel thermocouples were used for the ion pump air line measurements, and monitored on a separate instrument.

The sample breaker and contactor were mounted on the oven base, in the vacuum tank, as shown in Figure 44. This view shows the various connections, thermocouple leads, air line (for heat sink cooling) and so on, in detail. The overall equipment, set up for the heat run test, is shown in Figure 33.

Results of the heat run test are reported in some detail in Appendix E. In summary, the AC contact temperature rise was about 95°F (53°C) when carrying 600 amp in a 1000°F (538°C) environment and with a heat sink mounting surface maintained at 1015°F (546°C).

The DC contactor capsule temperature rise over the 1000°F ambient value was 55°F. However, the heat sink temperature also went up, due no doubt to heat from the nearby AC breaker, so the actual rise above the sink temperature was only 10°F.

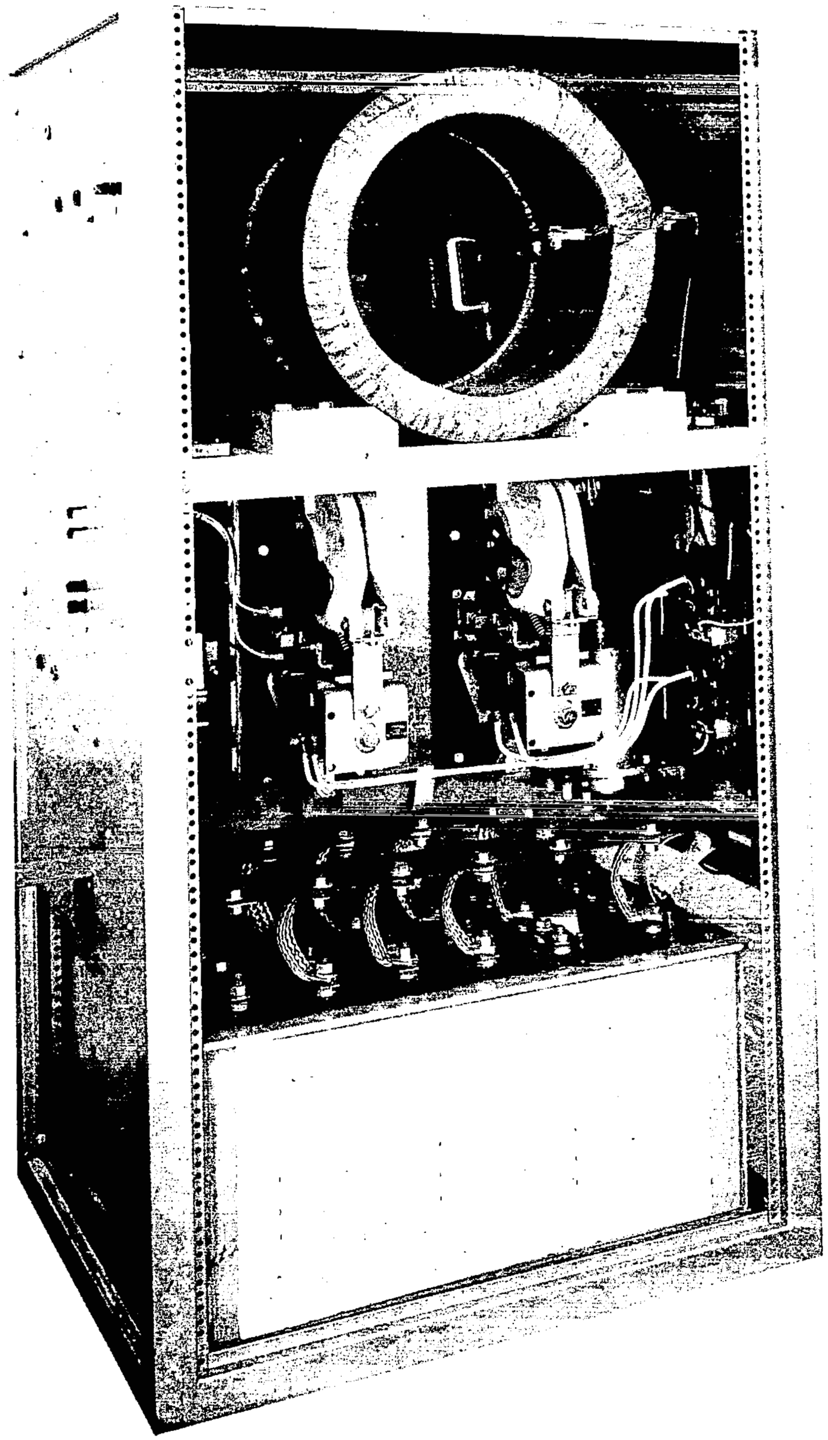


Figure 38. Main Power Supply Cabinet for Switchgear Interruption Tests, Showing AC Test Capacitors in Lower Section, Selector Contactors in the Center with Bus and Shunt, Inductance Coils at Top, and the Input Panel on the Left Side.

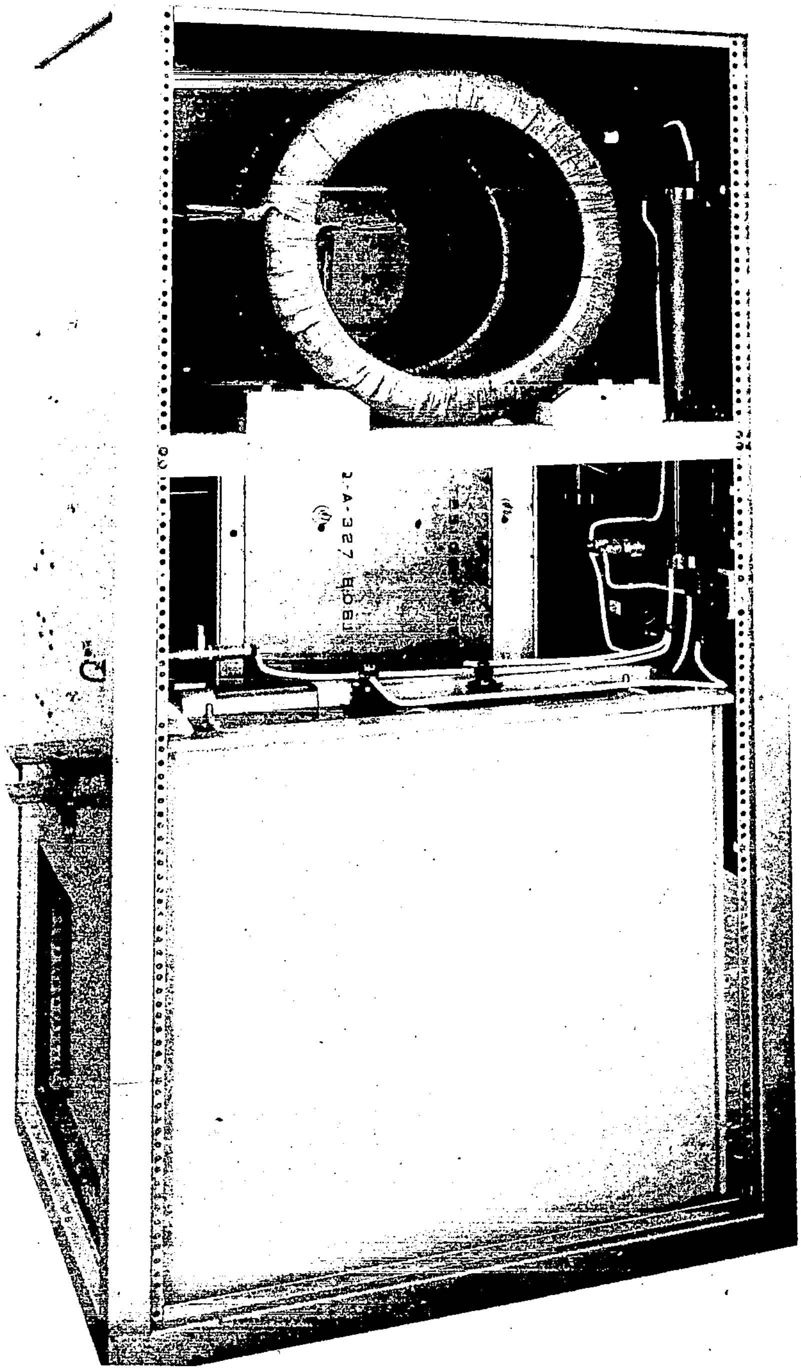


Figure 39. Main Power Supply Cabinet for Switchgear Interruption Tests, Showing Output Connections on Left Panel and DC Test Capacitors in Lower Section of Cabinet with DC Conductors, Shunt, and Resistor above Capacitors.

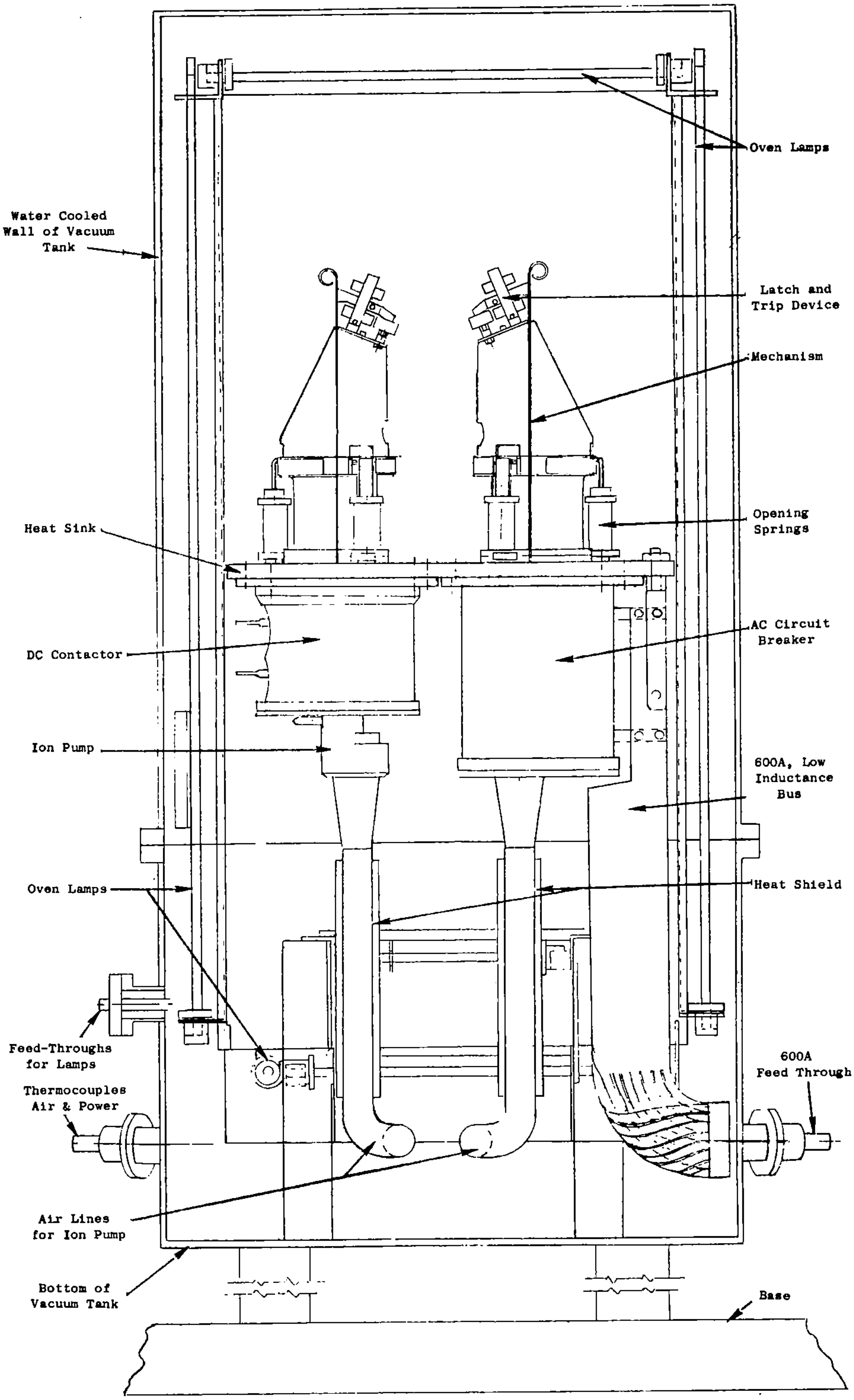


Figure 40. Sketch of Section Through CIV Vacuum Tank and Special Oven, with Vacuum Breaker and Contactor in Planned Position.

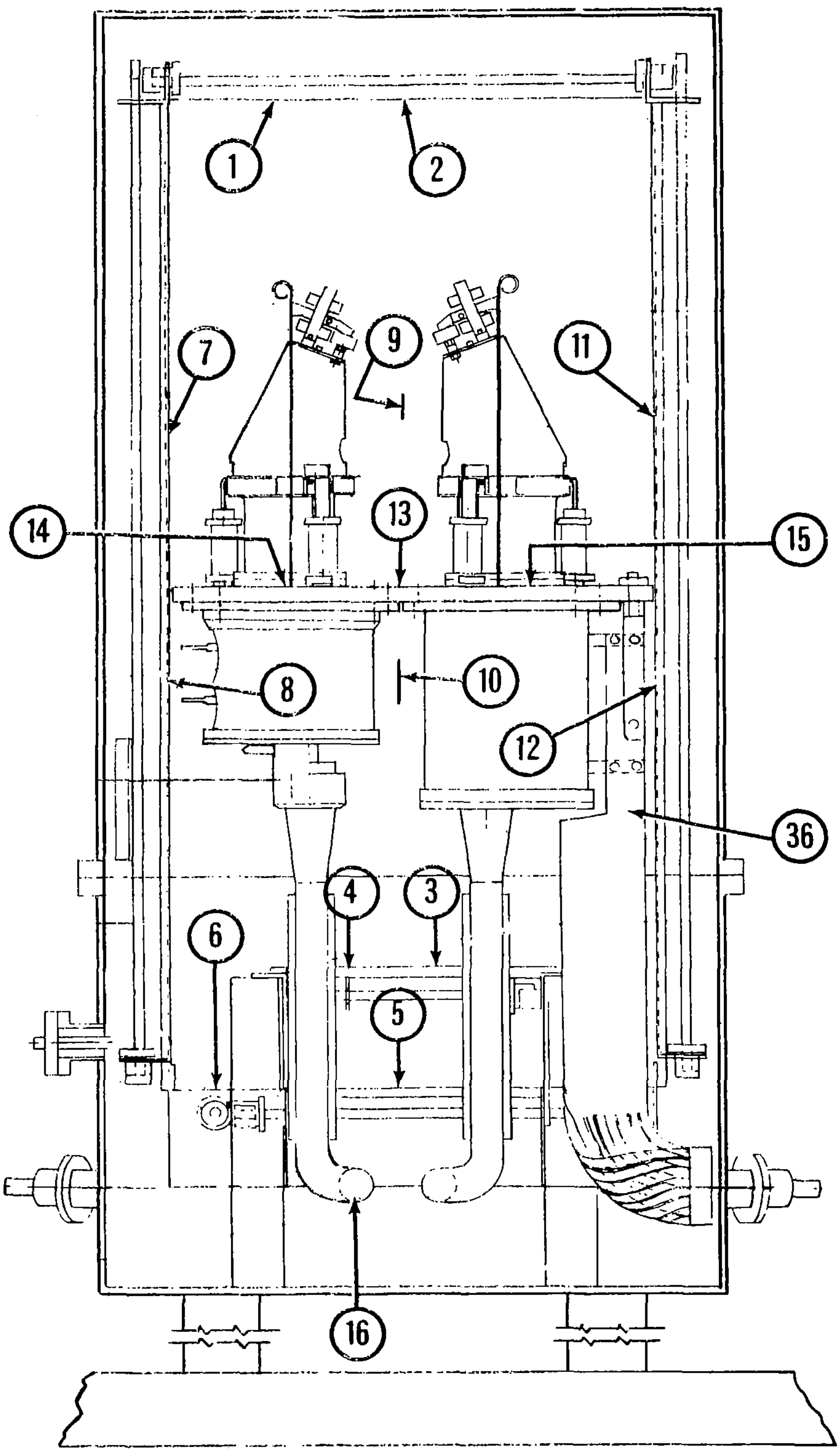


Figure 41. Location of Thermocouples in Various Parts of the Special Oven for the Heat Run and Endurance Tests.

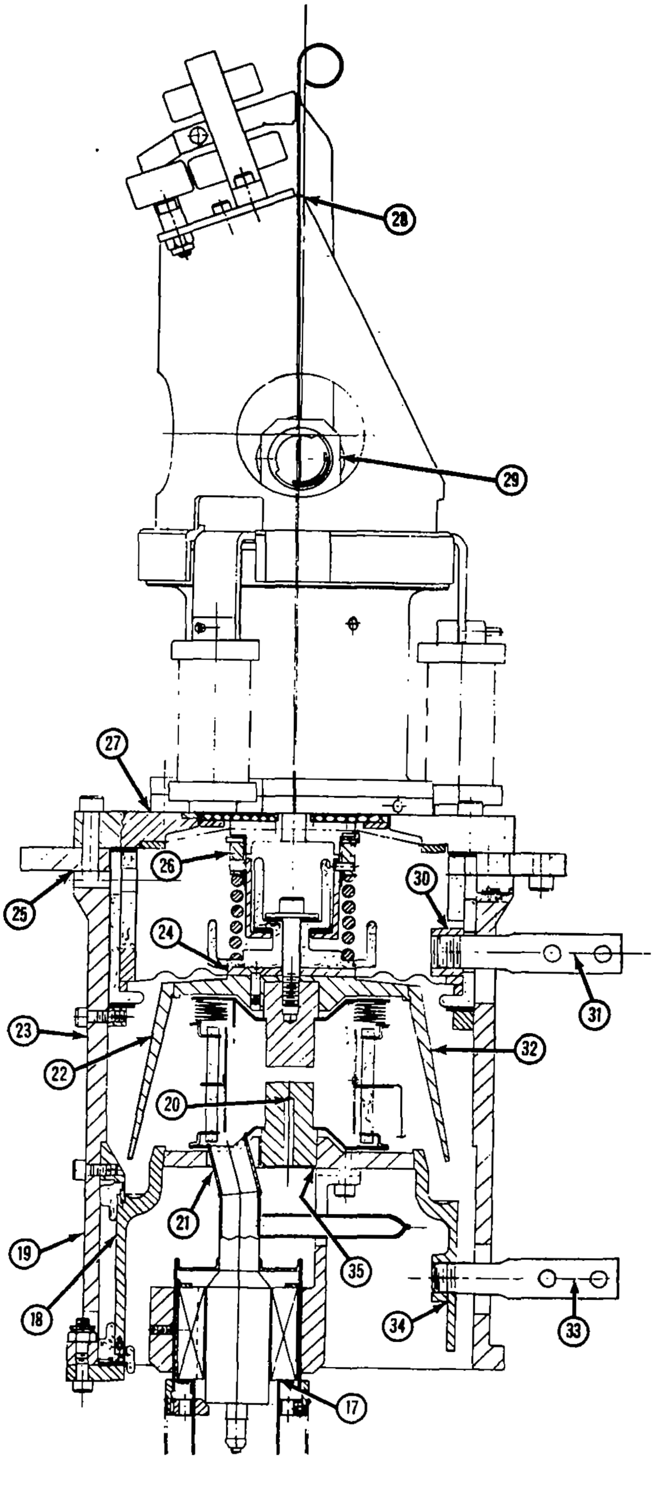


Figure 42. Location of Thermocouples on the AC Breaker for Heat Run and Endurance Test.

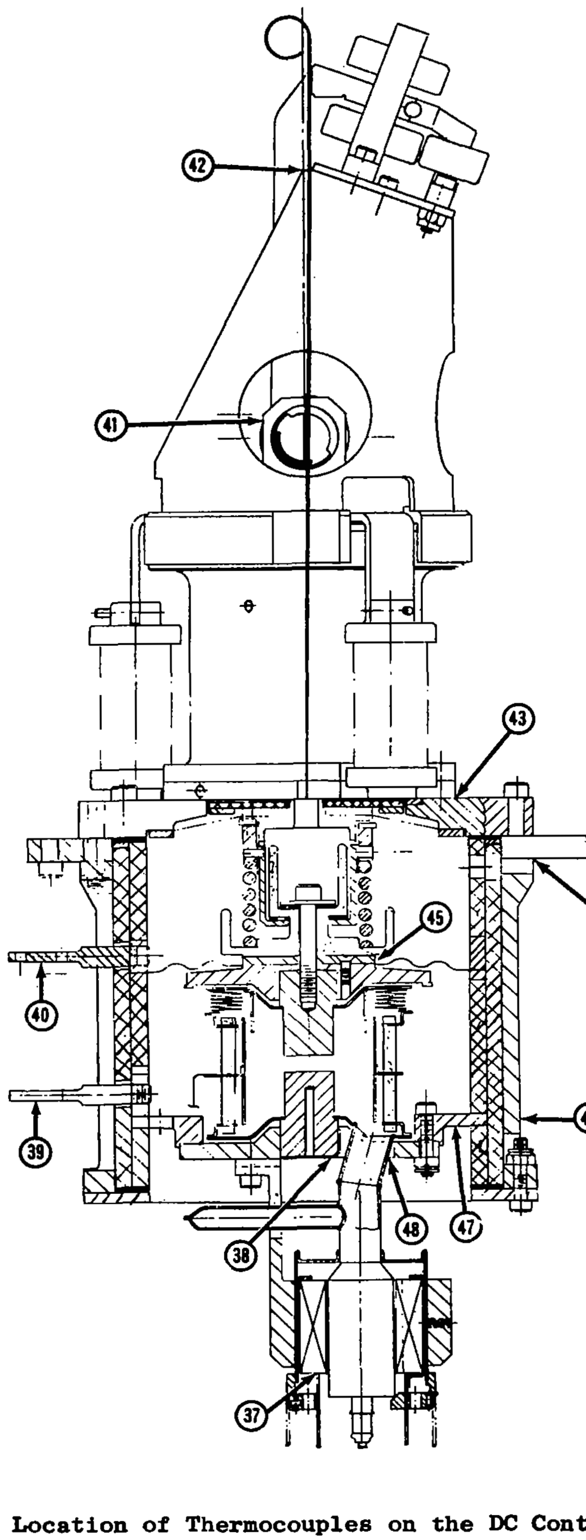


Figure 43. Location of Thermocouples on the DC Contactor for the Heat Run and Endurance Test.

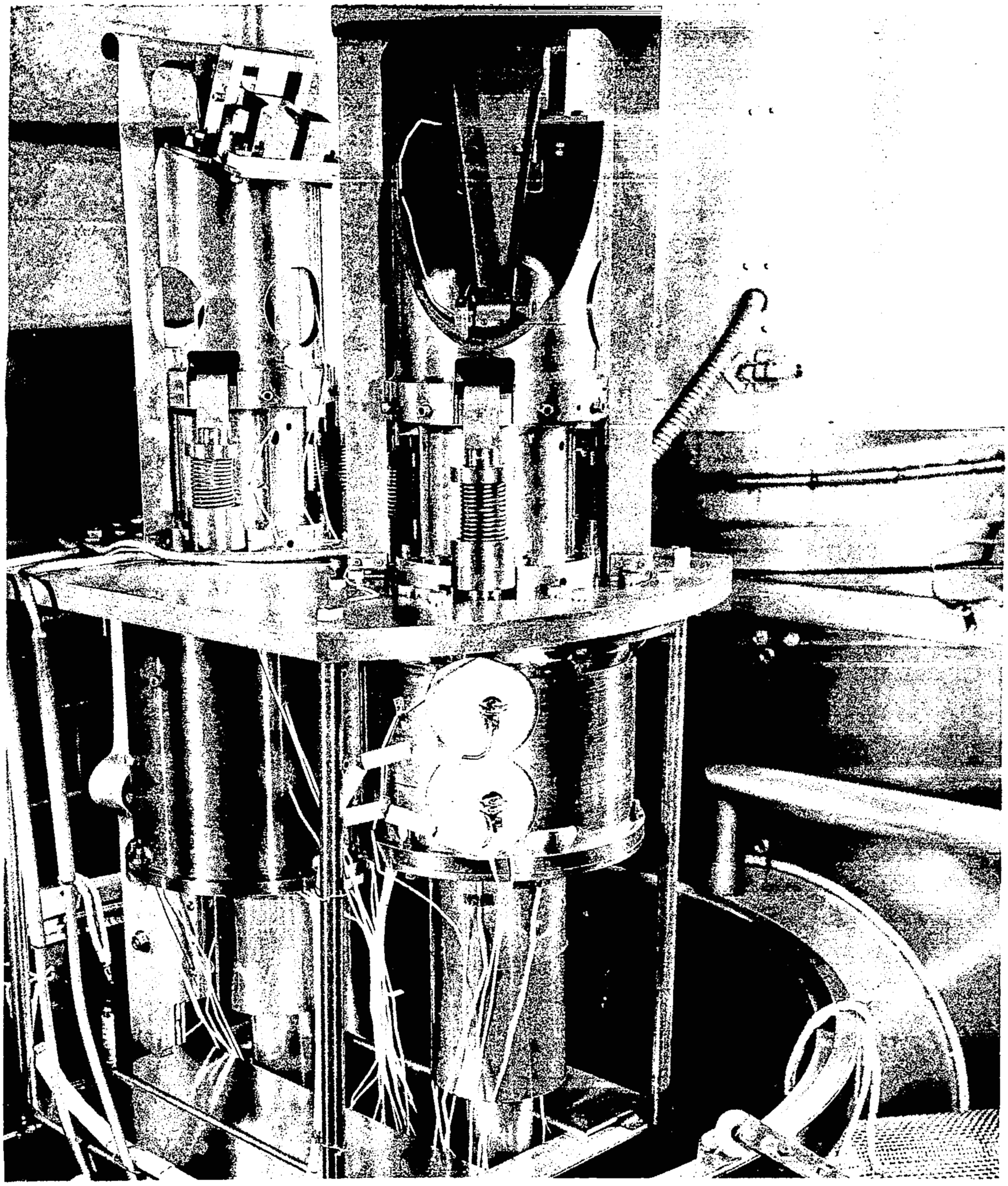


Figure 44. Close-Up of AC Breaker (Left), and DC Contactor Set Up in Vacuum Tank, with Heat Sink Supported on Oven Bottom, Just Before Closing Up for Heat Run Test.

Both the capsule temperatures were lower than expected, and the AC results were especially encouraging, for they indicated the heat radiating areas could be reduced.

D. High Voltage Leakage

The breaker and contactor were given high voltage leakage tests immediately after the heat run was completed. Additional tests were also made as the endurance test progressed, and at the close of the test, to obtain additional data. Results of the leakage tests are given in some detail in Appendix E.

The voltage for testing both samples was applied across the capsule surfaces (and gaps) by attaching the high voltage line (negative) to the center spinning which supports the shield around the contacts. The capsule contacts were closed, and grounded for the test.

The AC tests indicated that initial low withstand (high leakage) values gradually improved until at the end of the 1000 hour endurance test the capsule would easily withstand 2 KV (DC) with a leakage of only 0.5 milliamperes.

The DC tests were less satisfactory. At the start of the series, a maximum of 8.1 KV could be held, but leakage was 3.5 ma. Attempts to increase the voltage further, resulted in increased leakage but no higher voltage. As the endurance test progressed and further leakage checks were made, the withstand voltage value went down, until at the end of the test essentially no voltage could be held. The ceramic insulation (in the capsule) had apparently been contaminated.

Subsequent checks of the capsules from the breaker and contactor showed surface impurities, including gold, copper, and nickel, plus darkened areas that were due possibly to insufficient cleanliness during manufacture of the ceramic parts. The metal may have come from the braze or metallizing that was used, or been deposited by the test voltage that was applied.

New ceramic assemblies were designed and built for the interruption tests that will be discussed in Section VI-G. The data showed that these units would withstand full test voltage (1.6 KV DC on breaker and 12 KV on DC) after some conditioning in vacuum at 1000°F. The initial voltage tests indicated a low leakage current up to about 5 KV DC but after numerous momentary splits (or apparently momentary high current leakage) the withstand value increased until the 12 KV capability was reached. Thus a high degree of cleanliness and appropriate surface conditioning is indicated as a requirement.

E. Endurance Test

The endurance test started immediately after the contact temperature had stabilized and the heat run was completed. General procedures for this test are indicated in Appendix D. Results of the endurance test are given in Appendix E of this report, with temperatures at critical points during the test being shown in Tables I and II of that Appendix (Pages 119 & 120). During the test the the oven lamp current and temperature held very steady and the millivolt drops across the breaker and contactor contacts were essentially unchanged.

The samples suffered definite discoloration of parts when compared with the condition before the test. Nickel parts were colored blue, stainless steel was somewhat grey, and copper was a pinkish red color. Many of the bolted joints had pressure welded together and it was impossible to remove some of the stainless bolts which had not been lubricated before assembly. The compression springs (wipe and opening) had taken a set and the flexural pivots had sagged slightly. The contacts had not welded, and both units opened easily.

F. Mechanical Tests

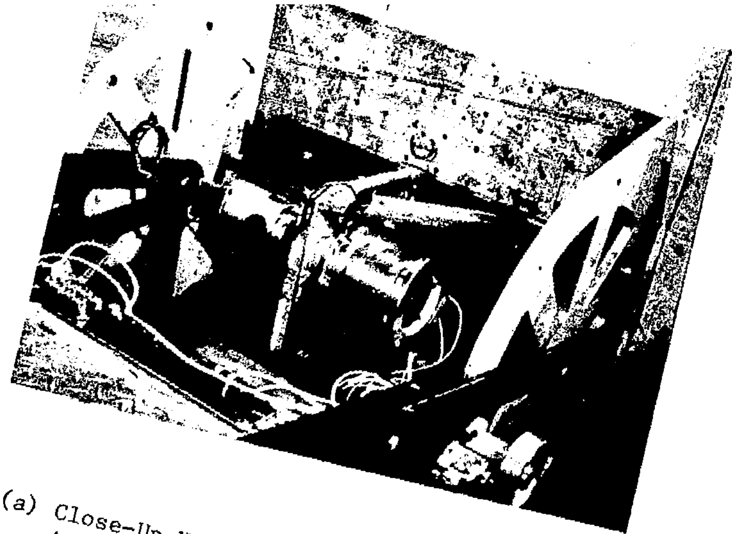
The mechanical tests were designed to simulate expected launch environmental conditions of the Saturn IB vehicle. Four tests (Acceleration, Acoustic, Vibration, and Shock) were performed and the test procedures are described in some detail in Appendix D. Test samples were the units which had been endurance tested.

Results of the mechanical tests are given in limited detail in Appendix E. However, the following briefly summarizes the results.

1. Acceleration Test

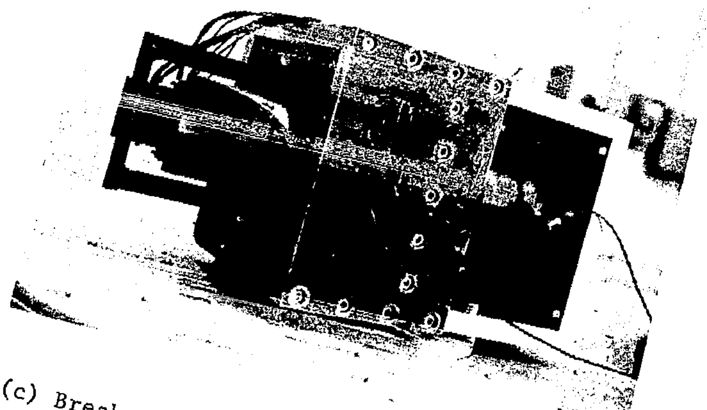
The acceleration test was performed on the DC contactor at an acceleration of 7 g's. Set up and arrangement for the test is shown in Figure 45(a).

The test was conducted with the contactor mounted in 6 positions. There was no failure or difficulty from this test. The launch latch coil provided adequate power to keep the mechanism in the closed position.



(a) Close-Up View of Contactor On Support, Attached to Test Bed of Accelerator

(b) Overall View of Set-Up With Sample in Front of Horn, and Microphone Below.



(c) Breaker on Heavy Aluminum Support Mounted Horizontally for Vibration Test.

(d) Breaker Mounted on Shock Machine for Hammer Blow From Top.

Figure 45. Arrangement of Test Samples for Mechanical Tests.

2. Acoustic Noise Test

The test to check the effect of intense noise on the DC contactor was made with the device suspended in front of the noise generator, as shown in Figure 45(b). Figures 46(a) and 46(b) are copies of the noise spectrum analysis that was made during the tests, and indicate a maximum level of 147 db over a broadband random spectrum of 20-9600 cps.

There was no discernable effect on the contactor. The launch latch held the mechanism toggle in the closed position at all times.

3. Vibration Test

The test to determine the effect of the required vibration spectrum was made on the AC breaker that had been endurance tested. Figure 45(c) shows the set up and one of the three positions in which the sample was tested, in accordance with the levels shown in Appendix D.

Tests with the breaker on the vertical axis of the test machine seemed most severe, and resulted in the loosening of the small screws holding the ceramic insulators which support the capsule. The flexible toggles also went into severe vibration and resonance at several frequencies, but tests for the required time at those frequencies did not cause damage. The launch latch coil was energized, and needed, for this test to keep the unit closed.

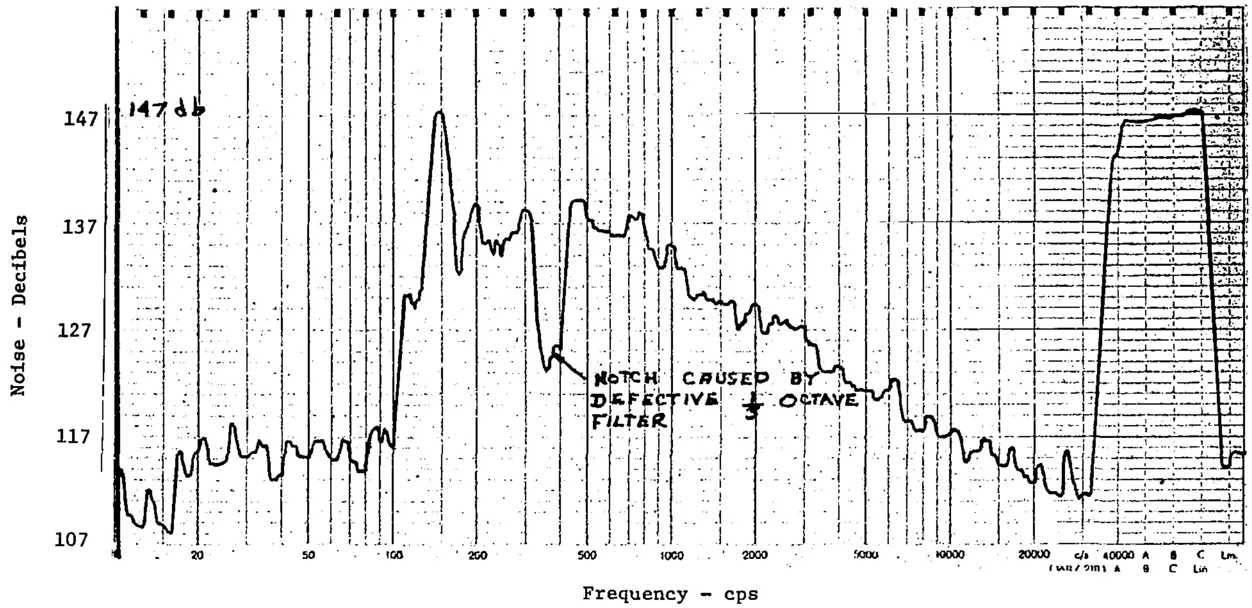
4. Shock Test

Tests to determine the effect of the 20 g shock blows in 6 directions were made on the AC breaker, in the set-up shown in Figure 45(d).

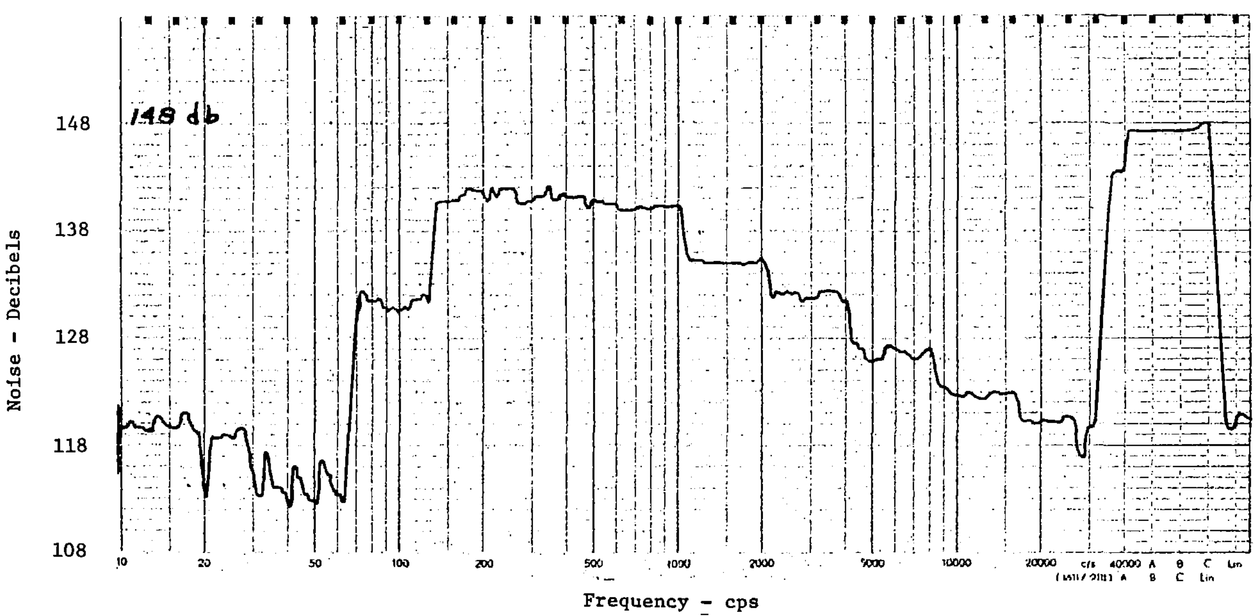
This test, with blows to provide 20 g minimum, was not particularly severe and no failure of any part was observed. The launch latch coil was energized, and needed, especially for the blow perpendicular to the breaker axis.

G. Interruption Tests

After completing the mechanical tests, the breaker and contactor were rebuilt using a new design of ceramic seal assembly for the vacuum capsule, and with special high temperature coils in the mechanism. These new parts will be discussed in detail before commenting on the tests.



(a) Noise Spectrum Analysis on Basis of 1/3 Octave Band.



(b) Noise Spectrum Analysis on Basis of Octave Band Readings.

Figure 46. Actual Plots of Noise Spectrum Analysis During Acoustic Test of AC Breaker.

1. New Design Parts

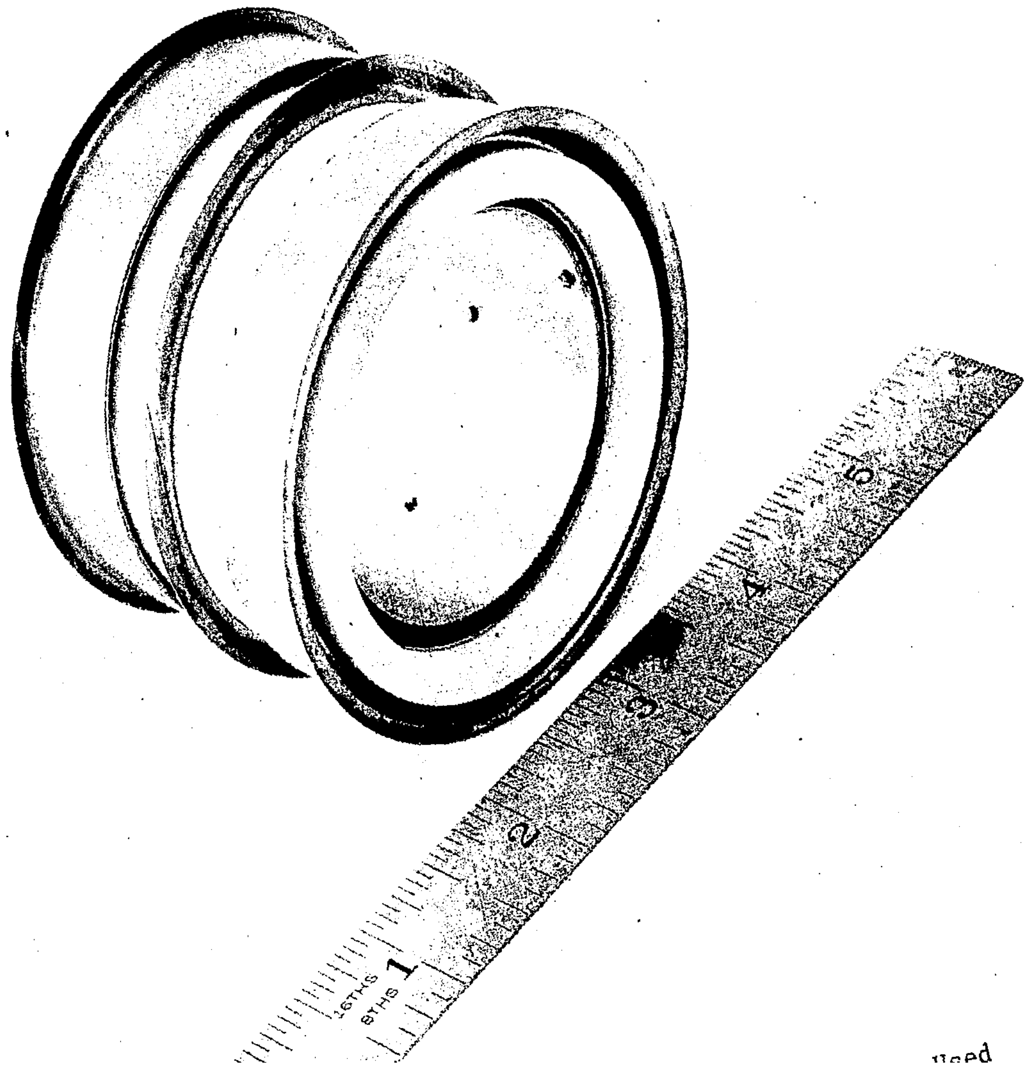
The ceramic assembly was redesigned to provide increased flexibility in the spinnings (to reduce the metal-ceramic joint stress) and a new type of metallizing (molybdenum-manganese instead of titanium hydride). The new assembly is shown in Figure 47. Special care was taken to maintain clean surfaces, and the results of subsequent voltage tests indicate the goal was achieved.

It was required that the interruption tests be made in vacuum at 1000°F (583°C). Therefore, special closing and tripping coils had to be developed for this application. One set of the coils is shown in Figure 48.

The special coils were made of "Anadur" coated, nickel clad silver wire, with "Anaflex" tape insulation next to the stainless steel bodies, and "Anacap" potting compound between turns and layers. The trip coil bodies were made of .015" thick stainless steel with the closing coil body of .030" thick stainless. A number of 1/8" diameter holes in the coil forms provided lower eddy current loss and aided in gas evolution during processing.

The insulating system was basically developed by the magnet wire research facility of Anaconda Wire & Cable Co. The system was processed in air in a series of bake-outs at temperatures up to 700°C (1292°F). However, the Anacap is not a good "adhesive" material and is brittle in thin sections. Thus there was much flaking off during operation and at least the trip coils should be completely encapsulated in a suitable holder in the future. Resistance values of the coils taken before, during, and after baking are given below:

Coil #	Air Dry	At 250°C (482°F)	At 500°C (932°F)	At 700°C (1292°F)	Room Temp.
Trip Coils					
2	.104	.173	.280	.310	.104
3	.105	.179	.268	.310	.105
4	.105	.186	.268	.310	.105
5	.104	.188	.268	.313	.105
Close Coils					
1A	.893	1.589	2.750	2.950	.893
2A	.885	1.630	2.620	3.00	.884



Used

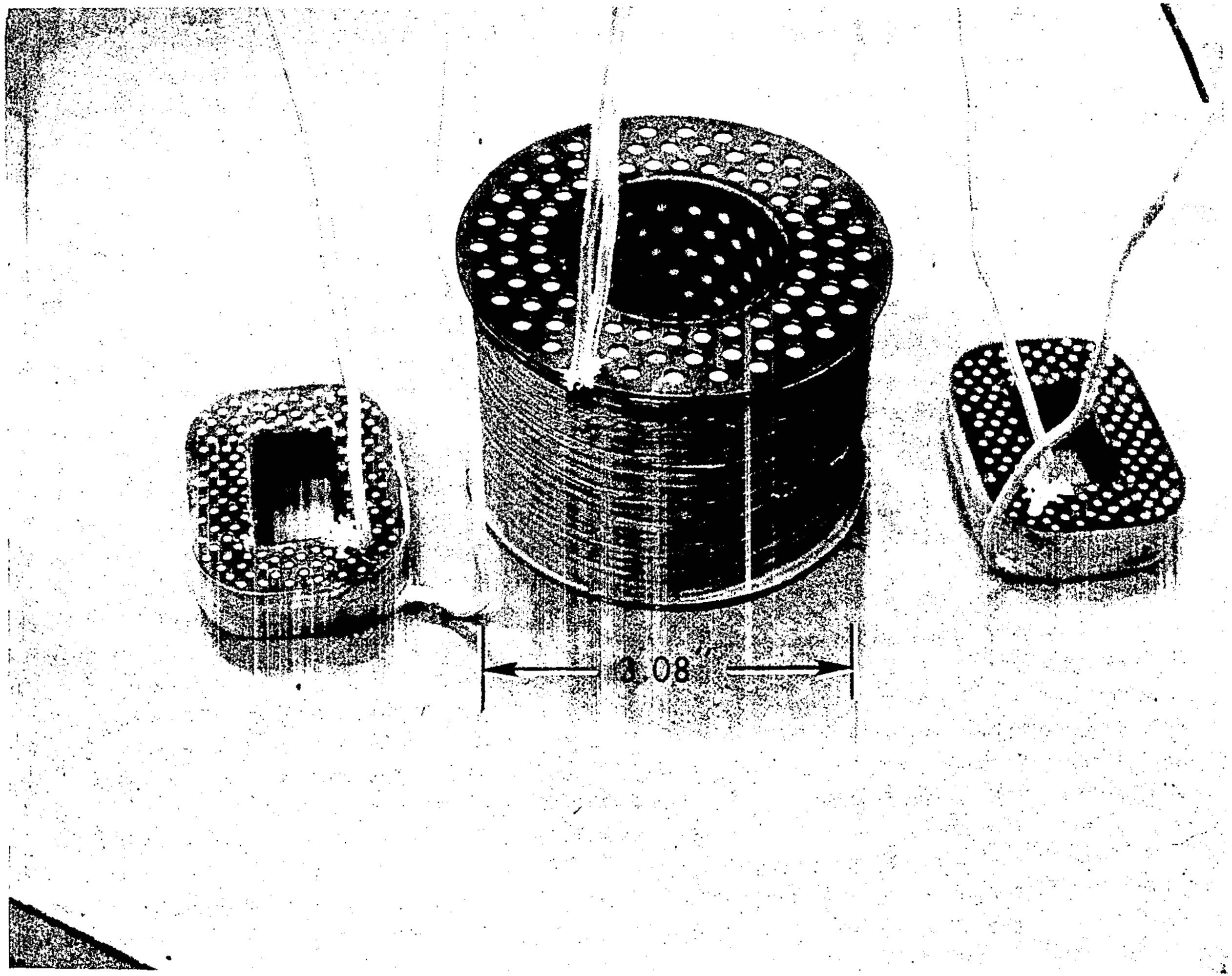


Figure 48. One Set of High Temperature Operating Coils for Switchgear Actuator (Mechanism), with Closing Coil in Center, and Trip Coils on Both Sides.

2. Interruption Tests

The new parts, along with available unused parts, were used to build up the new AC breaker and DC contactor. The breaker had a sealed capsule with ion pump, the same as in the original endurance test sample. The contactor capsule was baked out and then left capped but unsealed, so as to be open to the vacuum tank during test.

Figure 49 shows the test samples, mounted on the heat sink on the oven base. The leads for the test power to the contacts are visible, connected to the terminals of the samples.

An overall view of the set-up for the interruption tests is included as Figure 50. This shows the samples in the vacuum tank base at the right, along with the power supply cabinets, control equipment, oscillograph and DC power supply.

Tests were conducted in accordance with procedures described in Appendix D.

A summary of the interruption test activity is included in Appendix E. The results of over 200 tests showed there is no apparent problem which adversely affect the ability of the DC contactor to close and interrupt its rating (10 amperes, 10,000 volts). However, the DC power supply voltage decrement, because of the slow operating speed of the contactor, limited the test recovery voltage to a maximum of 8.1 KV. The AC breaker closed satisfactorily on the required value, or higher (up to 2000 amperes at 1200 volts), but no opening tests were obtained due to the slow operation of the breaker and low "Q" of the test power supply.

Subsequent no-load timing tests showed that the toggle mechanism caused erratic operation with close-open times of 50 to 150 milliseconds. However, similar tests without the toggles in place, and proper close coil voltage (applied from a charged capacitor) showed consistent close-open times of 20 to 25 milliseconds even with the weakened springs. This indicates the design changes that will provide suitable operation.

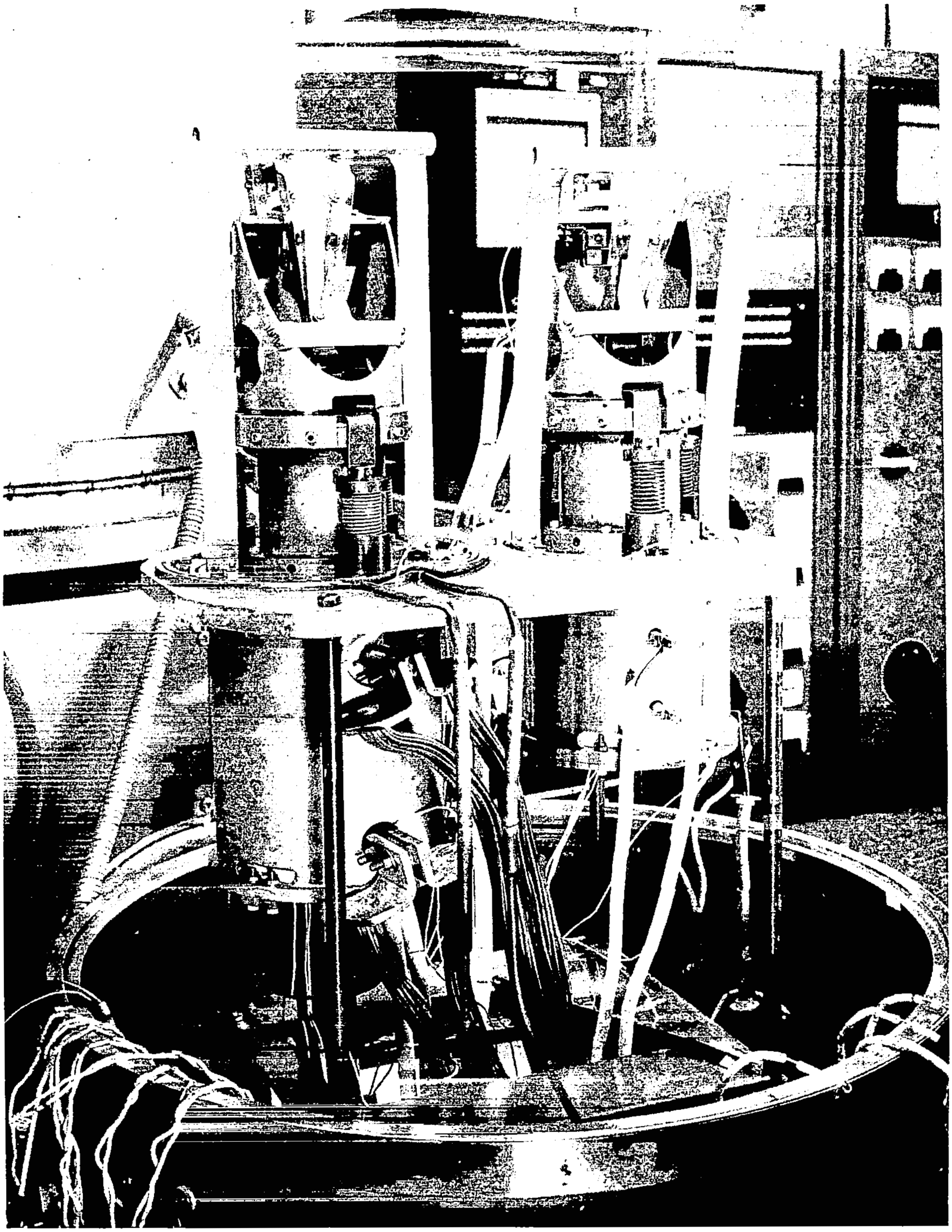


Figure 49. Test Samples Mounted in Vacuum Tank with AC Breaker at Left (Closed), DC Contactor at Right (Open), Showing Power Leads to Terminals.

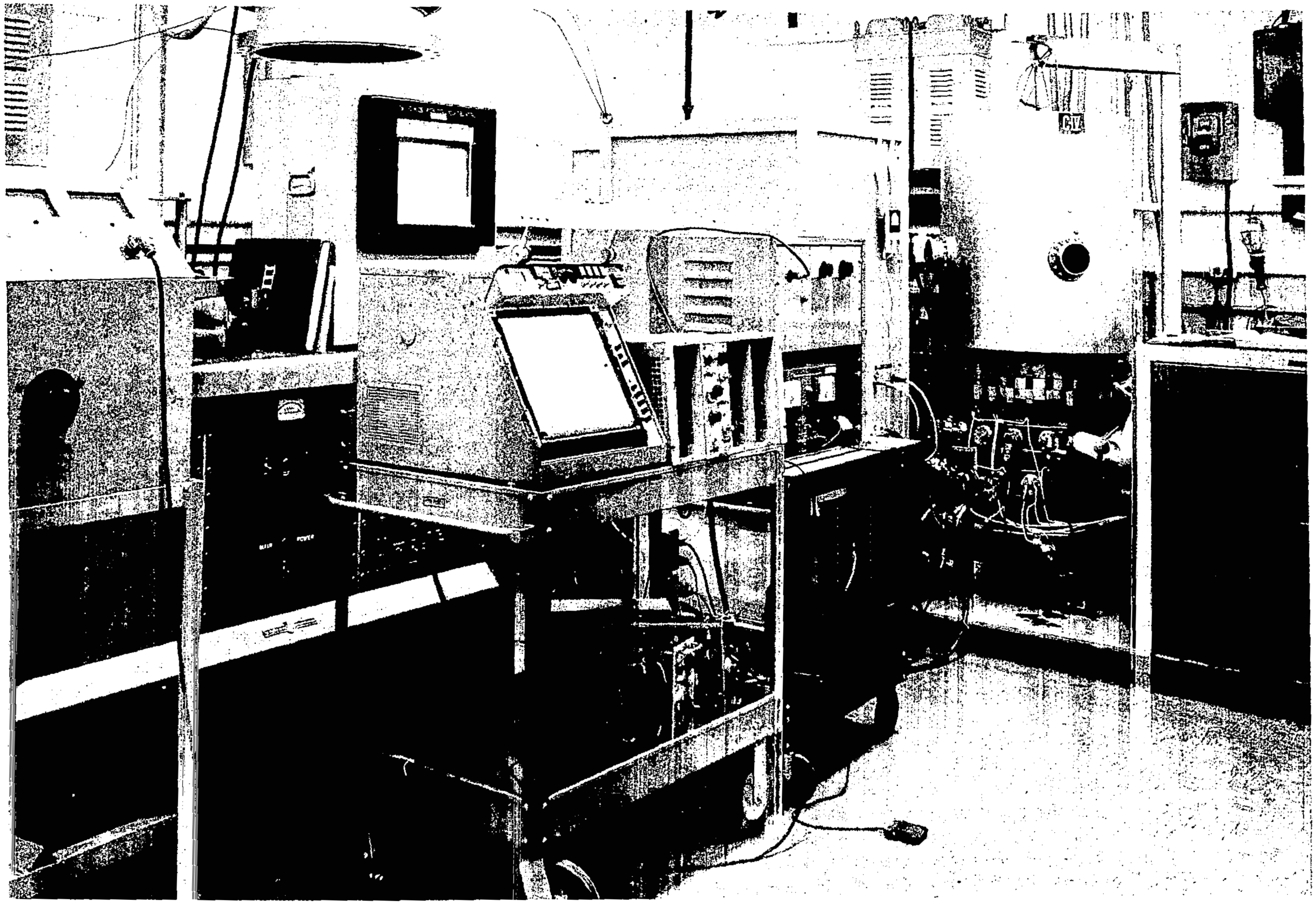


Figure 50. Overall View of Interruption Test Set-Up with High Voltage (10 KV DC) Supply at Left, Oscillograph and Controls in Center Foreground, Power Supply Cabinets in Center Background, and High Vacuum Test Tank with Test Samples at the Right.

VII. CONCLUSIONS AND RECOMMENDATIONS

This report has described the extensive material, processing, mechanical and electrical design problems that were encountered and solved in developing a preflight type AC breaker and DC contactor for large nuclear space power systems. The work has involved new technologies and areas of operation which had never been covered previously. The results met essentially all the original goals, making this a successful research and development program.

Based on the accomplishments from this effort, there was no apparent reason why the proposed ratings of 1000 volts, 600 amps, 2000 cps for the AC breaker and 10,000 volts, 10 amps DC for the DC contactor could not be attained in smaller and lighter flight type designs. However, several specific areas require additional investigation to accomplish the full AC interrupting objectives.

A design improvement is needed to increase the speed of operation of the switchgear units as well as to obtain consistent close and open times. The slow and inconsistant operating times of 50 to 150 milliseconds were caused primarily by the relatively slow action of the toggle actuating mechanism. For reliable operation over long periods of time, the loss of operating force of the Inconel X wipe and opening springs, experienced during the 1000 hour 1000° F endurance test, must be corrected in future work. A desirable goal is to open the circuit in 10 milliseconds, ± 1 ms., after the trip impulse is given. On a 2000 cps basis this would be 20 cycles, a value which is not too low for high speed switching and limiting of damage from short circuits.

Synthetic test circuits were used in testing the devices developed in this contract since rotating generators of sufficiently high frequency and power were not available. Full scale testing with a rotating generator would be desirable, in order to duplicate full system operating conditions such as power factor and distorted current and voltage waveshapes. The use of similar synthetic test circuits is common practice in testing the larger utility type circuit breakers which exceed available rotating power sources. Means to increase the "Q" value of the AC test power supply should be investigated for future testing.

VIII QUALITY ASSURANCE

A comprehensive quality assurance guide and program was developed and used in purchasing the raw materials and checking all parts obtained for the test samples. Careful analysis of the materials was particularly important because of the required high temperature operation and need for low outgassing in the vacuum environment.

The Q.A. guide defined three classifications of information, and the letters A, B, and C were used to indicate on drawings the degree of inspection detail required. Class C involved only a general check of dimensions and appearance while B and A required specific noting of the dimensions or material characteristics that were so marked.

All testing was specified to be done with calibrated (traceable to the U.S. Bureau of Standards) instruments. Dimensions were checked with recently calibrated gages and measuring devices.

A system of record keeping was also established by the guide to identify the inspected parts in stock, and to provide a system for rejection and replacement or rework if necessary. The Q.A. program proved to be both workable and necessary to accomplish to desired results, and will be recommended for future similar development programs.

APPENDIX A

CLEANING, HANDLING, BRAZING, AND WELDING PROCEDURES

FOR ASSEMBLY OF THE VACUUM CAPSULE

1.0 SCOPE

This document describes the general cleaning, handling, brazing, and welding procedures to be followed in assembly of the vacuum capsules for the Switchgear Program.

2.0 CLEANING PROCEDURES

2.1 General. All parts shall be free of dirt, grease, or other extraneous material. The final cleaning procedures described below shall be applied immediately prior to assembly.

2.2 Rodar

Machine Surface. Wash in free-rinsing detergent followed by degreasing with acetone and rinsing in ethyl, methyl or isopropyl alcohol.

Light Scale. Parts shall be immersed for 20 seconds in a solution containing 50 gm of ferric ammonium sulfate, 30 ml of H_2SO_4 (1.84 sp.gr.), 150 ml of HCL (1.16 sp.gr.), 150 ml of HNO_3 (1.42 sp.gr.), and 670 ml of water maintained between room temperature and 140°F. Residual acid shall be removed by rinsing with deionized water. Repeat as necessary.

2.3 Am Zirc. Parts shall be immersed for 30 seconds in an aqueous solution containing 50% by volume HNO_3 (1.42 sp.gr.) maintained between room temperature and 150°F. Residual acid shall be removed by rinsing with deionized water. Repeat as necessary.

2.4 Molybdenum. Parts shall be degreased with acetone, then cleaned by either of the following methods: (a) electrolytically by immersion in an aqueous solution of 66% by volume H_2SO_4 (1.84 sp.gr.) maintained at room temperature. Current densities of 100 to 300 amps/ft^2 shall be used with the molybdenum as the anode. Cleaning time shall be adjusted to obtain a uniform surface cleanliness. Residual acid shall be removed by rinsing with deionized water, (b) by an 1800°F/30 min. heat treatment in a vacuum furnace wherein the pressure shall be maintained at less than 5×10^{-5} torr during the thermal cycle. Parts shall be cooled to less than 150°F before removal from the furnace.

2.5 Braze Alloy. The Nicuro Type 80 braze alloy shall be degreased with acetone, followed by rinsing in ethyl, methyl or isopropyl alcohol.

2.6 Stainless Steel. Parts shall be degreased with acetone, followed by rinsing in ethyl, methyl or isopropyl alcohol. Pickle in an aqueous solution containing 25% by volume HCL (1.16 sp.gr.) at 75°F to 100°F for 1 to 2 minutes. Rinse with deionized water to remove residual acid. Repeat as necessary.

3.0 HANDLING PROCEDURES

3.1 Handling. After final cleaning and during all assembly operations the parts shall be handled with clean nylon or vinyl gloves.

3.2 Packaging. If storage is necessary, parts shall be sealed in polyethylene bags.

4.0 BRAZING PROCEDURE

4.1 Brazing Alloy Placement. Nicuro Type 80 braze alloy shall be positioned at each joint in adequate quantity to fill the joint. A stop-off compound, Nicrobraz green or its equivalent, shall be applied as necessary to limit braze alloy flow. If stop-off compound contaminates the braze joint, the joint shall be disassembled and recleaned before proceeding with braze assembly. After brazing, the stop-off residue shall be removed by dry grit blasting and wire brushing.

4.2 Brazing Cycle. Two Pt/Pt-10%Rh thermocouples shall be attached to the assembly near the braze joints on components which represent the heaviest sections being joined. During the brazing cycle, the temperature recorded by these thermocouples shall not differ by more than 20°F. Before applying heat to the assembly, a pressure of less than 5×10^{-5} torr shall be attained. During heating, pressure rises to 1×10^{-3} torr for short time intervals are acceptable. Pressure shall be maintained at less than 5×10^{-5} torr when the assembly is above 1000°F. The brazing temperature shall be 1700°F, $\pm$ 10°F for 2 minutes duration. The assembly shall be placed in a clean zirconium can, mimimum 0.010-inch thick wall, for brazing. Suitable supports shall be used to prevent direct contact between the assembly and the zirconium can. The brazed assembly cooling rate shall be approximately 10°F per minute from 1650°F to 1050°F. The assembly shall be cooled to less than 150°F before removal from the furnace.

5.0 WELDING PROCEDURES

5.1 Inert Arc. Tungsten inert gas welding shall be done using direct current, straight polarity. The torch gas cup shall be of adequate size to provide optimum gas coverage to the weld zone. Tungsten electrodes shall conform to ASTN B297-55T and shall be class EWTh-2. Welding shall be done in an argon filled chamber when the back side of the weld cannot be mechanically cleaned.

5.2 Shielding Gas. Argon of 99.95% minimum purity shall be used for both torch shielding and weld joint backup protection.

5.3 Filler Wire. The filler wire shall be that specified for the material to be welded.

5.4 Metal Vapor. Deposits of metal vapor produced by the welding process shall be removed by brushing with stainless steel wire brushes and rinsing with acetone and ethyl, methyl, or isopropyl alcohol.

5.5 Fixturing. Gas tungsten arc tack welds per paragraph 5.1 may be used to align the components prior to electron beam welding.

6.0 QUALITY ASSURANCE PROVISIONS

6.1 General. All welded and brazed joints shall be examined visually (10X). Joints shall be free from cracks, porosity, incomplete braze flow, undercutting, or non-uniformity.

6.2 Mass Spectrometer Leak Tests. Each welded or brazed joint shall be tested at a sensitivity of 5×10^{-10} std. cc/sec of air before inclusion in the next assembly. No leaks are allowed.

6.3 Packaging. The completed and accepted assembly shall be sealed in a polyethylene bag.

APPENDIX B

ASSEMBLY OF VACUUM CAPSULE FOR HIGH TEMPERATURE SWITCHGEAR

1) Preassembly Inspection and Cleaning

All molybdenum contacts and Rodar dishes were examined by "Dye-Check" penetrant and "Zyglo" penetrant inspection techniques for the presence of any surface imperfections. One molybdenum contact and one Rodar dish were found to be defective; all others were acceptable. Visual examination (up to 10X) of the remaining components indicated no other defective parts.

2) Fabrication - Welding and Brazing - End Pieces

The initial step was the inert gas shielded, tungsten arc welding of the stainless steel tube to the lower Rodar spinning. Four such joints were made, after which the integrity of the welds was determined by visual examination and helium leak testing.

The techniques used in brazing of both the upper and lower contact assemblies were the same, once the correct method (temperature measurement, braze alloy, braze alloy positioning, part positioning) of brazing was established through trials on one of the intended lower contact assemblies. Eight brazed assemblies were required (4 upper, 4 lower) for subsequent manufacture of four vacuum interrupter capsules. The following describes the procedures used and considerations taken which led to the successful fabrication of the assemblies.

With Amzirc (zirconium diffused copper) used for higher strength as compared with unalloyed copper, one limiting factor is the loss of strength or incipient melting if exposure temperatures exceed 1795°F. The maximum temperature expected in the vicinity of the brazed joints during operation of the switchgear was about 1500°F. Hence, the braze alloy used to join the Rodar-Amzirc-Molybdenum components must have a melting point in the 1500°F to 1800°F temperature range and exhibit adequate solubility with each of the parts being joined to provide satisfactory bonds. The braze alloy initially selected was 82Au-15Cu-3Ni with melting point 1670°F and brazing temperature 1700°F.

The cleaned Rodar-Amzirc-Molybdenum components of the intended first lower contact assembly were positioned and rings of the 82Au-15Cu-3Ni braze alloy were placed as required. The assembly was subsequently inserted in a zirconium enclosure which was lined with molybdenum foil to prevent contact of the Amzirc flange with the zirconium. The enclosed assembly was then exposed to a $1700^{\circ}F/2$ min. braze cycle, using a vacuum furnace with a pressure of less than 5×10^{-5} torr during the heating and cooling cycles. Temperatures were measured by means of a Pt-Pt/10%Rh thermocouple inserted through the zirconium can and into a machined well in the base of the molybdenum contact.

Upon removal of the brazed assembly from the furnace, it was observed that the Au-Cu-Ni braze alloy had not properly wet the surface of the molybdenum contact. Because copper and gold exhibit little if any solubility with molybdenum, the primary alloying with this member was expected to be achieved by means of a nickel-molybdenum reaction. However, the Au-Cu-Ni braze alloy contains only a 3% nickel addition which apparantly was insufficient for good wettability.

Therefore, a different braze alloy, 82Au-18Ni with a significantly higher nickel content but higher melting temperature was selected. The 82Au-18Ni alloy had a brazing temperature only 25° above its melting point (1760°), and acceptable filleting and flow of the alloy was obtained. All eight contact assemblies were therefore brazed with the gold-nickel braze alloy.

The lower contact assemblies (Serial No's 2,3,4,5) were all brazed satisfactorily with the 82Au-18Ni alloy, and post-braze helium leak testing of all assemblies indicated that no leaks were present. The only difficulty encountered was a slight distortion of the thin (0.020-inch) Amzirc shelf in the lower flange, apparently due to inability of this material to properly support the weight of the molybdenum contact while the assembly was at the brazing temperature.

The upper contact assemblies (Serial No's 1,2,3,4) were brazed in the same manner as the lower assemblies. Serial No's 3 and 4 were satisfactory by visual examination, and helium leak testing indicated no flaws. Assembly, Serial No. 2, also brazed satisfactorily but the molybdenum contact surface was not parallel with the Amzirc flange base and it was necessary to reface that contact surface. Contact assembly No. 1 had the Rodar dish tilted on the shoulder of the molybdenum contact, necessitating a rebraze cycle to correct the misalignment. The rebraze cycle was successful in realigning the Rodar dish. However, excessive erosion of the dish produced a small leak through the joint as indicated by helium leak testing. To achieve a vacuum tight assembly, a third braze cycle was used. A ring of the 82Au-15Cu-3Ni braze alloy was placed over the fillet formed by the 82Au-18Ni braze and the assembly after the third braze cycle indicated no leaks present. The surface of the molybdenum contact on this assembly also was not parallel with the Amzirc flange base and the contact surface was refaced.

3) Fabrication - Welding of Vacuum Capsule

One each of the upper and lower contact braze assemblies was positioned, along with a bellows and a ceramic seal assembly, in a special fixture developed to maintain alignment of these components while permitting rotation during welding. The initial step was to spot tack weld each member to the next adjacent member (upper dish to bellows, bellows to seal assembly, seal assembly to lower dish), after which the entire fixture was rotated 90 degrees to a horizontal position. Subsequent tungsten arc welding of the contact capsules was conducted in a vacuum purged weld chamber which had been back-filled with argon gas, as outlined in Appendix A. Post-weld helium leak testing of this first capsule indicated leakage less than 5×10^{-10} std. cc/sec of air.

However, visual examination did indicate that resistance spot tacking had produced small craters in the Rodar components. To eliminate these craters the components of the three remaining capsules were initially TIG tack welded (instead of spot tack welded), before the subsequent welding. These TIG tack welds, as well as the final welding, were all conducted in the previously mentioned vacuum purged, inert gas weld chamber.

All units were helium leak checked before proceeding with the evacuation, bake-out, and seal-off procedure described in Appendix C.

APPENDIX C

EVACUATION, BAKE-OUT, AND SEAL-OFF OF VACUUM CAPSULE FOR HIGH TEMPERATURE SWITCHGEAR

The completed capsule assembly including the ion pump and nickel evacuation tube was baked-out at $1200^{\circ}F$ for 25 to 30 hours. A special clam shell type furnace was constructed, using six 500 watt quartz lamps as the heat source, and placed around the capsule inside a vacuum chamber. The vacuum chamber, at a pressure of 10^{-5} torr, or lower, provided protection from oxidation to the outside of the capsule during bake-out, while the inside of the capsule assembly was evacuated through a tube to an external pumping system consisting of a liquid nitrogen cooled sorbtion pump and a 25 liter per second ion pump. A maximum temperature of $360^{\circ}F$ was maintained in the capsule pump by placing a water cooled copper coil around the pump assembly.

Pressure measurements inside the capsule were read at the external pumping system. Because of conductance limitation of the evacuation tube, pressure in the capsule assembly was calculated to be approximately 100 times the external reading. The pressure in capsule 4-5 (which was used for the AC circuit breaker) was 1.2×10^{-8} torr (based on the external pumping station readings) before turning on the furnace for bake-out. After a 25 hour bake-out and slow cooling to room temperature, the pressure was 1.0×10^{-8} torr but back-filling the chamber with air caused the pressure to rise to 1.6×10^{-8} torr, indicating a very small leak. A vacuum leak sealer (silicone resin GE SR-82 and Xylol solvent) was painted on the suspected metal to ceramic joint, and cured at $400^{\circ}F$ for 1 hour. The capsule pressure after cooling was 8.4×10^{-9} torr, so it was ready for pinch-off sealing of the nickel evacuation tube.

Several trial pieces of annealed nickel tube had been pinched-off using a hydraulic powered pinch-off tool. Leak testing of these trial joints with a helium mass spectrometer, showed them to be leak tight. After pinch-off of the capsule tube the pressure dropped to 4.8×10^{-9}, indicating very minute leakage of the capsule assembly which was easily overcome by the small ion pump on the capsule assembly. The pinch-off sealed capsule assembly was then transferred to the electron beam weld chamber, where it was permanently beam welded at the pinch.

Capsule 3-2 (which was used for the DC contactor) was baked-out under the same conditions as 4-5. The pressure before bake-out was 1.1×10^{-8} torr, but after bake-out the pressure was down to 5.6×10^{-9} torr, which was lower than was achieved with capsule 4-5. Back-filling the chamber with air brought the pressure up to 1.3×10^{-6} torr, indicating a larger leak. Application of the vacuum leak sealer to the lower Rodar disk joint brought the pressure down to 4.4×10^{-9} torr. Pinch-off and seal weld was made as with capsule 4-5 with equally good results.

APPENDIX D

SPECIFICATIONS AND PROCEDURES FOR THE SET-UP AND PERFORMANCE OF THE TESTS ON THE SWITCHGEAR

General

This document will describe in general terms the requirements for all the mechanical and electrical tests to which the switchgear samples were subjected. The preferred procedures for set-up and performance of the tests will also be described. The information will be divided into sections which cover each of the tests, with suitable cross reference where applicable.

Heat Run

The test on both the AC breaker and DC contactor will be made in a chamber providing a pressure of 10^{-6} torr (or lower) with a suitable oven to maintain the samples at 1000°F (538°C). Temperature of all critical points such as contacts, terminals, enclosure (shell) and mechanism are to be recorded, preferably with Platinum-Platinum 10% Rhodium thermocouples.

Power to the devices must be of the value specified (10 A for the DC contactor, 600 A, 2000 cps for the AC breaker) and arranged for constant output.

During the test, periodic readings of all thermocouple values, of the current flowing in the samples, the voltage drop across contacts and vacuum chamber feed-throughs is required. Use calibrated meters (checked to Bureau of Standards reference), and automatic thermocouple recording.

High Voltage Leakage

Use same set-up as for the Heat Run test. Arrange to connect a suitable high voltage conductor from the center (floating) shield of the switchgear vacuum capsule to a source of power. For the AC breaker use a maximum of 2000 volts, 2000 cps, and for the DC contactor a DC source of 20,000 volts. Place a suitably protected milliameter in each circuit to measure leakage current.

Make sure the switchgear terminals are grounded, and then slowly raise the test voltages to the required values, measuring leakage current at several voltage steps. Some type of "conditioning" may be involved (i.e., momentary spitting and breakdown) to obtain highest value. Record voltage and leakage current values.

This test to be made after the Heat Run, and after the Endurance tests.

Endurance

This test is essentially a continuation of the Heat Run test. After completing the Leakage Test, arrange for continuous monitoring of all temperature measurements and frequent check of the current through the contacts. Also, maintain heat sink at the required 1000°F, and the oven lamps at a current to provide the same temperature on parts of the switchgear which are most remote from the contacts.

Continue the test for the required length of time (1000 hours) with frequent check of all circuit parameters, reporting the results on the thermocouples at key points.

Mechanical Tests

The vibration and shock tests are to be made with the AC breaker mounted on a heavy aluminum support that is in the form of a rectangular box for low resonance.

The vibration test will be made on a Model 91A Unholtz-Diehy test machine and the following frequency and vibration levels will be covered, with the sample mounted in each of three axis positions.

Frequency -- Cps	Scan Level	Resonance Level
16 - 100	6 g	3 g
100 - 1000	0.0118 P/P	0.0050 P/P
180 - 2000	19 g	9.5 g

Each frequency range to be scanned in 5 minutes with a logarithmic frequency sweep at the vibration levels specified for the frequency range. Note major resonance frequencies and apply sine wave excitation for five minutes at the value noted above under Resonance Level

Check resistance of contacts before and after test, and any indication of contact opening during the test. After each test check for visible change.

The shock test will consist of six blows of at least 20 g along each of three mutually perpendicular axes. Use same support as for the vibration test.

Record the output of the accelerometers mounted on the anvil and the support. Check for mechanical damage and report any discrepancy.

Acceleration tests are to be made on a Genisco Model E-185 accelerator, with the test sample mounted on a heavy steel support. Arrange to mount the sample in each of 6 positions (on 3 axes) and subject it to a force of 7 g for 15 minutes in those positions.

Record any opening of contacts or change in mechanism position during the test. Inspect and note any mechanical damage after each test.

The acoustic excitation test is to be made with the sample contactor mounted on a heavy steel frame, suspended by "shock" (elastic) cord in front of the noise generating horn. Apply an intensity of 148 DB for a duration of 5 minutes with the output measured on a Bruel Kjaer sound pressure level recorder. Level to have a tolerance of $\pm$ 3 DB over the range of 1/3 octave center band frequency from 20 to 2000 cps.

Monitor contact closed condition and determine any change during the test. Inspect after test and note any part damage or failure.

Short Circuit

Set up samples on the heat sink, in the vacuum tank and oven, in the same manner as for the Heat Run test. Arrange to check temperature at key points. Connect control power to the operating coils. Furnish test power of the required current and voltage as required to provide the following values at opening of contacts, on a close-open test.

AC breaker - 1000 volts, 2000 cps, 1200 rms amps
DC contactor - 10,000 volts, 10 amps, DC

Arrange to record, with a permanent record type oscillograph, application of close coil current, voltage before contacts close, current while contact is closed, application of trip coil current, contact parting time, and recovery voltage across contacts. Note tank vacuum and temperatures of key points on the sample.

Make a series of interruption tests, starting at 25% of rating, and going to 50 and 100% of rating if results are satisfactory. A total of 25 full duty cycles is to be made at full interrupting rating.

APPENDIX E

SUPPLEMENTARY RESULTS OF TESTS ON SWITCHGEAR BREAKER AND CONTACTOR

General

This document will include the results of the mechanical and electrical tests, specified in Appendix D, in limited detail. The information will be presented in the same sequence as the test specifications.

Heat Run

With the oven, heat sink, and switchgear at approximately 1000°F in the test tank and a pressure of about 2×10^{-6} torr, current was passed through the contacts until a steady temperature was obtained. Temperature rises for the two samples, above the 1000°F ambient, are given below:

	Measurement Point	Total Rise, °F
A.C. Breaker	Contact Surface	110
	Top of Capsule	80
	Upper Terminal	110
	Bottom of Capsule	100
	Lower Terminal	125
	Upper Radiator	85
	Outer Shell (near radiator)	55
	Heat Sink (near shell)	15
D.C. Contactor	Top of Capsule	50
	Bottom of Capsule	55
	Terminals	35
	Heat Sink	45

Temperature rises were less than originally expected. Note that hottest spot above the heat sink mounting plate temperature was only 110°F in the A.C. Breaker and 10°F in the D.C. Contactor.

High Potential

Samples and environment were the same as for the Heat Run test. Power from a 35 KV DC test set was attached, through a milliammeter, to the 25 KV high voltage feed through, which in turn was connected to the floating shield of the DC contactor vacuum capsule. For the AC breaker test, a 5 KV DC test set was initially used to check leakage, with suitable connection through a 5 KV feed through to the capsule floating shield. Tests on the AC unit were eventually made with a 2000 cps test voltage.

The AC unit initially (after the Heat Run) would withstand only 400 volts, with a resulting leakage of 0.5 ma, and beyond this voltage the current increased rapidly. However, after 6 days of the Endurance Test it became possible to apply as much as 4 KV DC, with a leakage current of only 1 milliampere. A high voltage 2000 cps test source was then attached, and a maximum of 1 KV could be held, with a leakage of 0.3 ma. No higher voltage was possible because of the test unit "built-in" resistor.

The DC unit initially could withstand a maximum of only 8.1 KV, at which point the leakage current was 3.5 ma. Subsequent attempts to recheck the withstand, resulted in lower values, and this condition continued to deteriorate until near the end of the test period a value of 500 volts could not be held.

NOTE: Subsequent inspection indicated a deterioration of the capsule seal assembly, ceramic surface, which apparently accounted for the voltage withstand limitation.

Endurance

This test was started immediately after all desired data was obtained from the Heat Run test. Arrangements were made to automatically and continuously record all thermocouple outputs, while making hourly checks of vacuum tank pressure, current through samples, pressure in the capsules, and terminal voltage drops.

Temperature values for typical thermocouples at selected times during the 1000 hour endurance test period are given in Tables I and II. Referenced thermocouple locations are given in Figures 41, 42, and 43 of this report.

TABLE I

TEMPERATURE READINGS - AT CRITICAL POINTS DURING ENDURANCE TEST

Thermocouple Numbers - (See Figures 41,42,43 for Location)

DATE AND TIME	1	6	12	15	20	23	24	31	33	38	39	43	45
5-11-66 1700	1070	075	1100	1010	1055	1040	1080	1085	1035	965	955	1075	1025
5-12-66 1600	1060	980	1095	1010	1045	1020	1060	1075	1035	955	945	1070	1015
5-16-66 1630	1070	980	1088	1015	1060	1035	1068	1068	1040	965	950	1070	1015
5-20-66 1730	1070	980	1095	1015	1060	1037	1077	1090	1045	977	950	1075	1020
5-24-66 1630	1060	970	1088	1015	1055	1030	1065	1085	1045	985	960	1075	1023
5-27-66 1700	1070	980	1088	1015	1060	1035	1070	1085	1042	975	955	1075	1023
5-21-66 0630	1068	990	1088	1015	1060	1035	1067	1080	1050	978	958	1080	1023
6-3-66 0635	1068	980	1088	1015	1060	1035	1070	1090	1050	977	958	1080	1027

Notes:
1. Tank pressure varied from 1.4×10^{-6} to 3.0×10^{-7} torr during this period.
2. All temperatures in degrees Fahrenheit.
3. Test currents through samples were: Breaker-600A, 2000 cps; Contactor - 10A DC.

TABLE II

TEMPERATURE READINGS - AT CRITICAL POINTS

DURING ENDURANCE TEST

Thermocouple Numbers - (See Figures 41,42,43 for Location)

DATE AND TIME	1	6	12	15	20	23	24	31	33	38	39	43	45
6-4-66 1440	1068	980	1088	1060	1070	1035	1088	1095	1055	982	978	1088	1035
6-9-66 0635	1060	980	1088	1015	1053	1035	1068	1088	1046	965	944	1079	1025
6-10-66(1) 1500	1079	980	1060	1035	1088	1052	1095	1088	1068	1000	963	1093	1035
6-13-66 0630	1072	974	1070	1015	1068	1043	1088	1105	1055	993	960	1088	1033
6-16-66 0630	1072	980	1060	1025	1069	1043	1088	1105	1060	1003	965	1096	1038
6-20-66 0630	1068	965	1060	1015	1070	1038	1084	1105	1055	980	960	1088	1035
6-22-66 0800	1072	962	1060	1033	1069	1043	1078	1105	1065	989	970	1095	1043
6-23-66 0945	1068	962	1052	1015	1052	1035	1078	1100	1058	975	958	1095	1030

Notes:
1. Test tank pressure reduced to atmosphere between 1230 on June 9 and 0500 on June 10, due to failure in tank ion pump feed-through. Reading at 1500 shows stabilized condition after shut-down. Otherwise, tank pressure was in 10^{-7} torr range.
2. All temperatures in degrees Fahrenheit.
3. Test currents through samples were: Breaker - 600A, 2000 cps; Contactor- 10A DC.

It was concluded that there was no measurable increase in contact resistance and heating due to the long time exposure to the heat and vacuum environment. The DC unit high voltage leakage increased during the test, although the AC unit value went down. Subsequent dismantling and inspection of both breaker and contactor showed no complete failure of parts although parts were discolored, the capsule ceramic surface was somewhat contaminated, and the opening springs had taken a major set with as much as a 45% loss of spring force.

Mechanical Tests

The samples were mounted as specified, on approved supports that would provide minimum resonance. Test results are given in the following paragraphs. Figure 45 includes pictures showing the mounting for each test condition.

The vibration test was made as required, with the AC breaker sample mounted on the heavy aluminum box-type support, on a Model 91A Unholtz-Dieky vibration test machine. Test values of frequency and excursion were as specified and listed in Appendix D.

Mounted vertically, the sample was resonant at 407, 813, and 1154 cps, and each point was held at 1/2 level for 5 minutes. No part breakage occurred, but two screws holding the upper capsule support blocks came loose, and there was much "dust" beneath the sample, apparently from the mica-mat spacers and ceramic.

Mounted in the horizontal plane (toggle arms in vertical plane) there was resonance at 137, 154, and 510 cps. Each point was held for 5 minutes at 1/2 scan level. The flexible toggle arms had excursions of as much as 1/2" and the loud "rattling" sound indicate parts rubbing together. There was also indication (as in the vertical position test) that the contacts were opening. No physical damage was noted.

The third vibration test was made with the sample horizontal and the toggle arms in the horizontal plane. Resonances were noted at 69, 802, and 860 cps and each point was checked for 5 minutes at 1/2 scan value. Contacts apparently opened some, above 1500 cps, and the flexible arms resonated as much as 1", peak to peak. No major damage was noted, but there was rotation of the capsule (and terminals), and more "dust" generated.

The shock test was made with the breaker on its fixture, attached to the heavy steel anvil of a Navy-type light weight shock testing machine. A Honeywell Visecorder was used to record the output of two accelerometers - one on the fixture and the other on the anvil.

In vertical position, blow toward side of sample (in plane of toggle arms), six blows of 24 g caused no detectable damage or affected operation.

In vertical position, blow toward side of sample (perpendicular to plane of toggle arms), six blows of 22 g caused no detectable damage or affected the subsequent operation in any way.

In vertical position, with blow from top (parallel to axis of sample), six blows of 24 g caused no detectable damage or affected the operation of the breaker.

Acceleration tests were made with the sample attached to a heavy steel mounting plate, which in turn was bolted to the test bed of a Genisco Model E-185 accelerator.

Tests as specified, provided a 7 g acceleration on the point of the sample furthest from the center of the machine. A series of 6 runs, with the sample mounted in both directions of three mutually perpendicular directions, and a time duration of 15 minutes for each test, resulted in no observable damage or subsequent misoperation. The holding coil was energized at all times, and was needed to keep the toggle from opening during the test.

The acoustic excitation test was made with the sample on the mounting fixture, which was in turn supported by 4 elastic "shock" cords directly in front of the exponential horn attached to the noise generator.

The noise generator was a Model 644 air chopper made by Noise Unlimited. Microphone and audio frequency recording equipment was made by Bruel & Kjaer, with the microphone checked with a B&K pistonphone.

Operating tests were made before and after the tests. No damage from the test or misoperation could be detected during or after subjecting the sample to a 5 minute duration of acoustic noise at a level of approximately 148 db. Copies of the noise spectrum analysis are shown in Figure 46.

Short Circuit

The AC and DC samples were set up in the vacuum tank, the same as was done for the Heat Run test, and thermocouples arranged to check a total of 24 points in the oven and samples. A special test power supply was developed to provide the high voltage DC and AC required by the test specifications given in Appendix D. Refer to Figure 50 for an overall view of the test set up and Figures 36 and 37 for the schematic diagram.

Suitable control circuitry was developed to provide close and trip coil current to the samples, to operate the power circuit switches, and energize the capacitor charging system. Arrangements were also made to record on a dry type oscillograph the required data and series of events during a test operation.

AC Breaker Tests. No load tests were completed with the sample at temperature, in vacuum. However, some difficulty was experienced with shorting of the trip coil turns to ground, and the operating times were both slow (up to 150 milliseconds to close) and erratic.

Closing tests were made with initial voltage of up to 1400 volts rms and initial peak currents up to 3000 amps, with a "ringing" frequency of 2000 cps. A copy of a typical "close" test recording is shown on the page following this text. However, because of unexpectedly low circuit "Q", the decay in current and voltage was excessive and only closing tests could be accomplished with the erratic timing of the available sample.

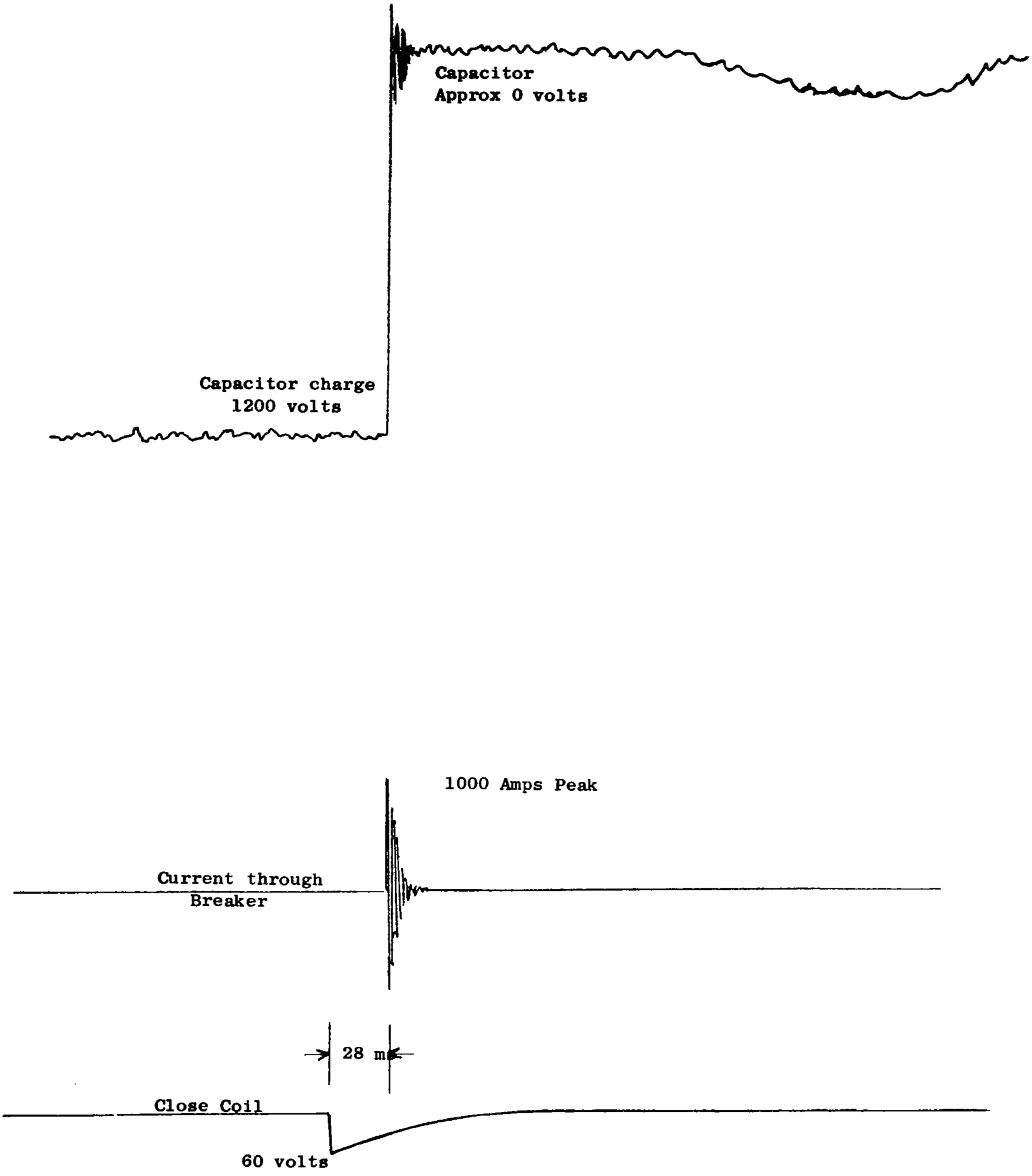
DC Contactor Test. No load tests were successfully completed with the sample at the environment conditions specified. However, the time to close was erratic (varying from 50 to 150 milliseconds) and occasionally the contactor would not latch closed.

Closing tests were made with initial voltage on the capacitor bank of as much as 12 KV, giving an inrush current of 12 amperes, DC (limited by a non-inductive resistor). The bank of six 6 KV high "Q" capacitors connected in series/parallel provided up to 24,800 joules at 12 KV.

The maximum power interrupted was 8.1 amps at 8.1 KV which resulted from a decay from the initial 11.8 KV charge, due to the length of time the contactor was closed. A copy of the oscillograph from a typical test is on the second page following this text. Higher voltages and current could apparently have been interrupted successfully, but failure of the 30 KV DC power supply necessitated using the only immediately available unit, which was limited to 12 KV.

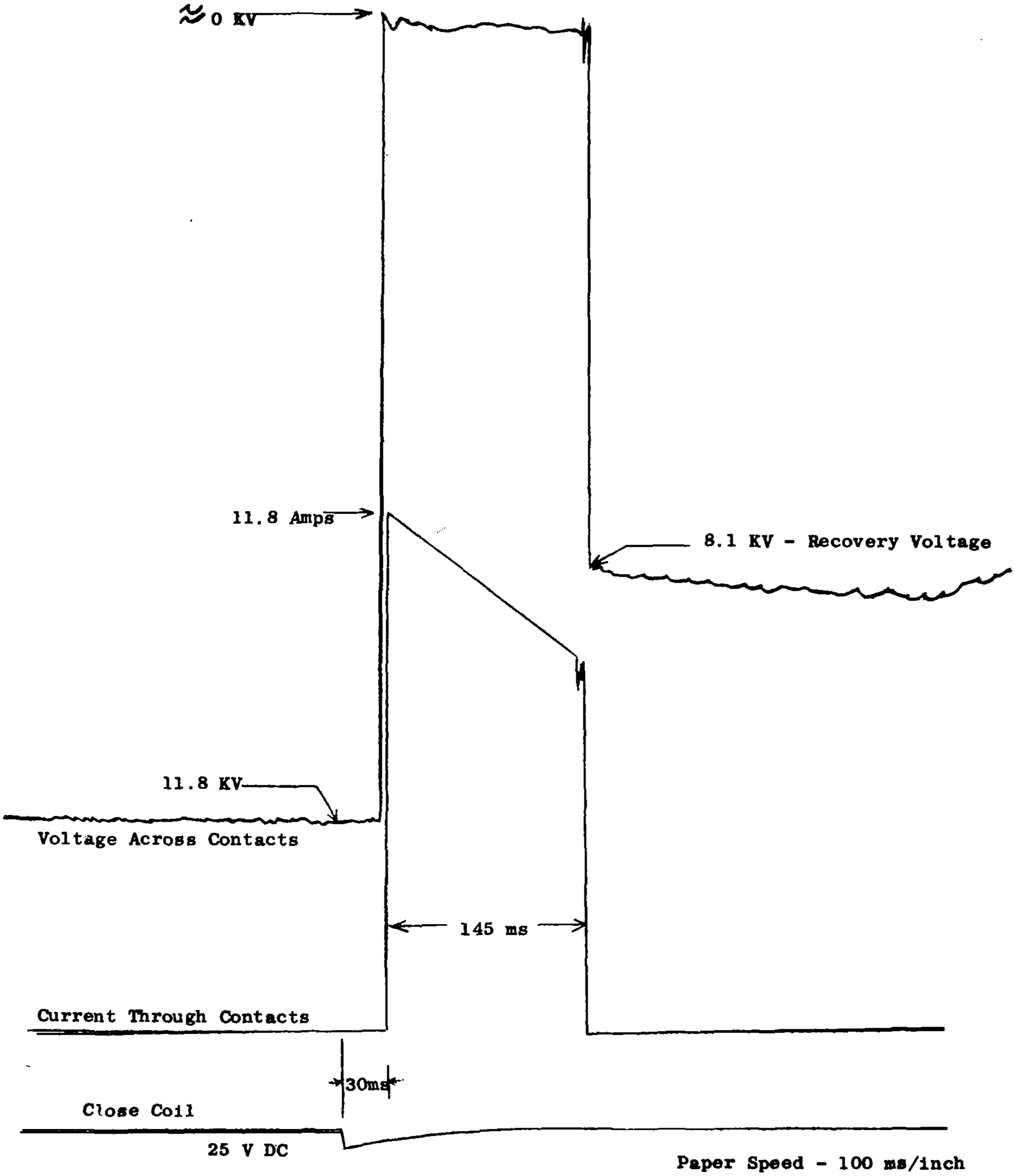
However, increasing the speed of operation in future samples to provide a shorter "close" time would leave more charge on the capacitors and thus provide a test current at interruption that is nearer the required value. One other item of concern is the apparent voltage breakdown at the charge voltage (several "spits" occurred during charging for the more than 100 tests). This will require improved design or processing of the ceramic insulation, where subsequent inspection showed the breakdown had occurred.

APPENDIX E



Copy of Oscillogram #5363

AC Breaker Closing Test



Copy of Oscillograph #5385

DC Contactor Close-Open Test

NASA-Langley, 1968 —— 3

"The aeronautical and space activities of the United States shall be conducted so as to contribute . . . to the expansion of human knowledge of phenomena in the atmosphere and space. The Administration shall provide for the widest practicable and appropriate dissemination of information concerning its activities and the results thereof."

—NATIONAL AERONAUTICS AND SPACE ACT OF 1958

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